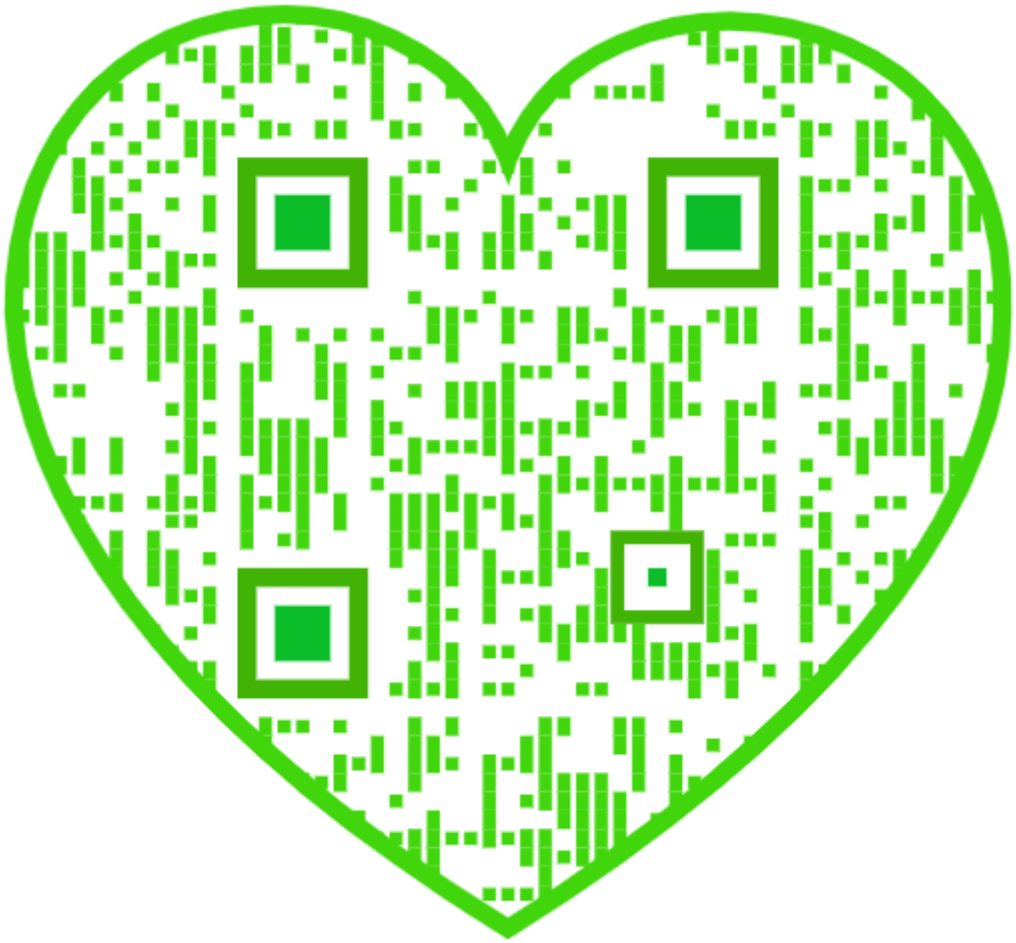

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THE DEPOSITS OF THE USEFUL MINERALS AND ROCKS

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THE DEPOSITS

OF THE

USEFUL MINERALS & ROCKS

THEIR ORIGIN, FORM, AND CONTENT

BY

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IN THREE VOLUMES

VOL. I

ORE-DEPOSITS IN GENERAL—MAGMATIC SEGREGATIONS
CONTACT-DEPOSITS—TIN LODES—QUICKSILVER LODES

WITH 291 ILLUSTRATIONS

MACMILLAN AND CO., LIMITED
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PREFACE

With the existence of the excellent and comprehensive treatises of ore-deposits by Beck and Stelzner-Bergeat it might appear doubtful whether a further treatment of the same subject was either necessary or justified. Although the intention of the authors to write a book dealing with the useful deposits existed before the appearance of the treatises above-mentioned, publication was delayed in order to avoid unproductive repetition. Since however the works of Beck and Stelzner-Bergeat bear the character of handbooks with numerous descriptions of separate ore-occurrences, a work does not seem superfluous which in text-book form concerns itself in the first place with the general and established results of geological inquiry into deposits, while treating the individual occurrences only in so far as they serve to illustrate and explain general principles. It must be added that the book we have in view will not be limited to the ore-deposits, but will take into consideration the economically far more important deposits of coal, salt, and mineral oil, so that all those minerals and rocks which come to be mined will be considered.

We are greatly indebted to our professional brethren for kind assistance in the provision of the material necessary for completeness and correctness.

THE AUTHORS.

Berlin and Christiania, *May* 1909.

TRANSLATOR'S PREFACE

The intention in making this translation was two-fold; firstly, to school myself in the matter of ore-deposition; and secondly, to place before British mining engineers and geologists an important work upon this subject, in a language with which, upon the whole, they would be better acquainted than with the original German.

In the first part of this intention I feel I have succeeded. With regard to the second I trust that the realization will not fall too far short. I have endeavoured faithfully to bring out both the fact and the spirit of the author's work, this being of such high standard that the reception of a translation must depend largely upon the degree of closeness with which the original is approached.

Only in the choice of English equivalents for German terms has there been any exercise of judgment on my part. Considering first the German term *Gang*, this may be translated either as 'lode' or 'vein.' Speaking generally, in the United Kingdom and British Colonies, the term 'lode' would be used for the larger, more continuous, and more inclusive occurrence, while 'vein' would be expressive of a less important unit, either by reason of smaller size, lesser regularity, or non-metalliferous character. Lode indeed is the equivalent of fissure-vein, than which however it is better, being essentially a mining term and in that sense parallel with the term 'ore.'

Speaking in 1862, H. C. Salmon[1] said, "I should consider that any metalliferous channel of ground with a definite direction and dip might properly be called a 'lode,' but the word has received a theoretical meaning implying exclusively a mineral deposit between the walls of an original fissure." Within that description, to which I think the great majority of

[1] *Mining and Smelting Magazine*, Cornwall, 1862.

British miners would subscribe, the character of a lode as a tabular deposit in connection with a fissure, is contained.

The relation of lode and vein may be illustrated by the following extracts. In the editorial of *The Mining Magazine*,[1] it is stated in reference to the Esperanza mine in Mexico, " Mr. H. A. Titcomb expressed the view that the branch veins ceased to be productive when they joined the main lode. . . ."

In the same editorial[2] when speaking of some deposits in Rhodesia it is said, " All of these may be described as masses of ferruginous shale, with pyrite in seams parallel to the foliation, the entire mass intersected by quartz veins, and all of it variously enriched by gold."

In the annual report of the company, known as the Tasmania Gold, for the year ending September 30, 1912,[3] it is stated that " the main lode varied in width from $2\frac{1}{2}$ to 7 feet . . . while the branch vein varied from $1\frac{1}{2}$ to 4 feet."

In describing the Bereozovsk gold deposit of the Urals, C. W. Purington[4] says, " The remarkable feature about the gold deposit of Bereozovsk is the occurrence of the granite dykes, above referred to. These are locally known as lodes, and may probably be so called as they are all more or less auriferous, although, so far as has been determined, not in a payable sense. The dykes have a north and south direction, and vary in width from 30 to 150 feet . . . their length varying from 100 feet to 3000 feet, along which lengths they have been worked for gold values. It should be made clear that the gold values occur in the beresite (the name given to the particular granitic rock of these dykes) only by virtue of the quartz veins which cross it, and which are worked by a series of short drifts connected by long adits or cross-cuts running lengthwise of the ' lodes ' or dykes. . . . There are literally thousands of the narrow short veins above referred to."

In the United States *Gang* would be translated as ' vein ' rather than ' lode.' The two terms however are used confusedly in that country as the following extracts show.

W. L. Tovote[5] says of the copper deposits at Clifton-Morenci, Arizona,

[1] *Mining Magazine*, October 1912, p. 243.

[2] *Ibid.*, June 1912, Vol. VI. p. 394.

[3] Abstracted, *Ibid.*, February 1913, Vol. VIII. p. 151.

[4] Bulletin No. 112, January 1914, Institution of Mining and Metallurgy, London.

[5] ' The Clifton-Morenci District of Arizona,' *Min. and Sci. Press*, December 10, 1910, 771.

" While the lode-type of vein is at present a dominant factor at Morenci, it is probably only of local character, limited by two converging faults. . . . Outside of this block the lode system breaks up into a number of fairly well-defined fissure-veins. . . ."

A. Locke comparing the Veta Madre, Guanjuato, with the Comstock Lode [1] says, " In the most genuine meaning of the term the two lodes are fissure veins . . . both . . . are enormous lode-like bodies of mixed quartz and rock, carrying scattered bonanzas."

J. R. Finlay [2] refers indiscriminately to the copper deposits at Lake Superior as lodes and veins. He says for instance that the " Calumet Lode . . . is the single conglomerate vein worked in the district." The other mines he says exploit ' amygdaloid lodes.'

C. T. Rice, describing mining practice at the copper deposits at Lake Superior,[3] says, " As considerable trouble has been encountered with some of the shafts within 30 feet of the vein, it has been decided that a footwall shaft should not be less than 60 feet from the lode."

F. L. Ransome, describing the occurrence of the gold-silver deposits at Goldfield, Nevada,[4] says, " certain deposits exhibit in part more regularity of form and there is reason to suppose that at depths greater than those now reached such approaches to lode-like form may become more numerous. But within the mass of rock extending from the surface to a depth of 600 feet, a mass which includes all the ore-bodies thus far exploited, the deposits cannot be called lodes or veins without giving to these words unusual meanings, or without ascribing to the mineralized bodies a tabular form that they rarely possess."

The balance of opinion in America would also appear to be that a lode is a fissure-vein, that is, one having a tabular form.

That original and proper meaning of the term has however received serious hurt from the necessity to apply a wider meaning suitable to the American law, and especially to that known as ' the law of the apex.' In the Smuggler case the judge stated that "A body of mineral or mineral-bearing rock in the general mass of the mountain, so far as it may continue unbroken without interruption, may be regarded as a lode, whatever the boundaries may be." It is however not generally held to be wise to allow

[1] ' Four Famous Districts Compared,' *Eng. and Min. Journal*, September 9, 1911.
[2] ' Appraisal of Michigan Mines,' *Ibid.*, September 16, 1911, p. 539.
[3] *Ibid.*, July 27, 1912, p. 171.
[4] *U.S. Geol. Survey P.P.*, No. 66, p. 150.

technical definitions to follow the necessities of the law, even when that law be of the best. Most Americans however consider that their mining law would be the better for revision. Hennen Jennings says,[1] "It would seem that our stupid apex law which was supposed to be so beneficial to the prospector and the poor man has really been a boomerang and struck back at them, for people with money are now fearful in the initial stages of a mining venture that they may be buying law-suits rather than ore-deposits."

Another view of what constitutes a lode is that held by T. A. Rickard, who says,[2] "Lode comes from the Anglo-Saxon *laedan* to lead. A seam, thread, crevice, discolouration, or mineral arrangement may constitute a lode. It is a comprehensive term for the rock structure or appearance that gives the miner a clue to the presence and direction of ore." Most people will however consider a lode to be something more tangible than a discolouration, a structure, or an appearance.

Again, if *Gang* be translated as 'vein,' how is the German word *Ader* to be expressed, the simple meaning of which is 'vein'? It is also worthy of consideration that 'lode' is essentially a mining term and the equivalent of *filon* in French and *veta* in Spanish; whereas 'vein' is primarily a physiological and secondarily a geological term, the equivalents of which in those two languages are *vein* and *vena* respectively.

Reviewing all these points it appears that though as a tribute to the prominent position taken by America in the study of ore-deposits the nomenclature of that country might be gracefully and advantageously followed, yet in this particular case judgment is best exercised by a return to the original conception of the term lode, namely, an ore-deposit of tabular shape occurring along a fissure or other line of disturbance.

When a vein, that is the filling between the two walls of a simple fracture, fulfils these conditions, it becomes a lode, such veins forming the greatest single class of lodes. But where the deposit consists of an assembly of veins, with or without impregnation or replacement of the intervening rock, a 'composite lode' is formed.

Similarly, when a dyke is metalliferous and a fitting subject for mining operations it becomes a lode, though for the purposes of distinction such a deposit may be spoken of as an 'intrusive' or 'differentiated' lode.

[1] *Min. Sci. Press*, January 3, 1914, p. 12.
[2] *The Mining Magazine*, May 1912, p. 324.

Zementationzone I have translated as 'cementation zone' in preference to 'secondary enrichment zone,' because the particular zone is not one which for all ores is synonymous with enrichment. Further, 'cementation' is the term used by van Hise,[1] and by its use the three terms 'oxidation,' 'cementation,' and 'primary,' remain the same in English as in German.

Seifen I have translated as 'gravel-deposits.' The group includes alluvial as well as eluvial deposits. The term 'gravel-deposit' is better than 'placer,' because in itself it is more descriptive of the nature of such deposits; moreover 'placer' is not much used in the United Kingdom or the British Colonies. To translate *Seifen* as 'detrital deposits' would have brought such beds as the Rand conglomerates within this group; while 'fragmentary deposits' would have included the breccias formed underground.

Sahlband, the clayey material often found on the walls of lodes, I would translate as 'gouge.' It is material which can be easily gouged.

Gangtonschiefer, the contorted slaty material often found in lodes, I have translated as 'flucan.'

I acknowledge with pleasure the assistance I received from my assistant J. C. S. Whittuck, Stud. I.M.M., in making this translation of Vol. I.

S. J. TRUSCOTT.

LONDON, *June* 1914.

[1] 'Some Principles of Controlling the Deposition of Ores,' by C. R. van Hise, *Genesis of Ore-Deposits*, A.I.M.E., 1901, p. 282.

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INTRODUCTION

THE study of the deposits of the useful minerals, concerning itself with the geological position, the shape, the content, and the genesis of those deposits, is a branch of geology. As long as shape and content only were considered and the deposit regarded as something independent and entirely foreign to the enclosing formation, this study was regarded as belonging to the art of mining. In distinction to this, modern investigation seeks before all things to determine the details of the geological position and the genesis of the deposit, of which two factors it considers shape and content are functions.

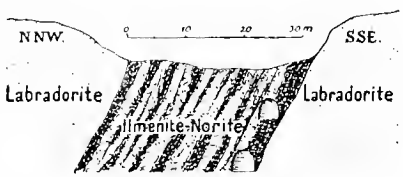


FIG. 1.—Magmatic segregation of ilmenite-norite at Soggendal, Norway. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 7.

The dependence of each ore-occurrence upon the sum of all its geological factors may be gathered from the following cases:

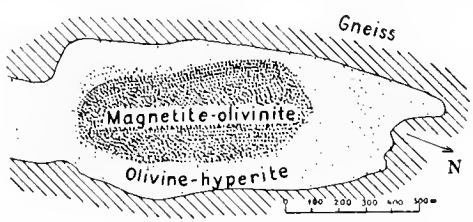


FIG. 2.—Sketch, somewhat diagrammatic, of the occurrence at Taberg in Sweden, showing the passage from olivine-hyperite in the peripheral portions of the eruptive mass to magnetite-olivinite in the central portions. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 7.

(*a*) Just as from the molten magma of a deep-seated rock such as granite, felspar and mica may in part separate in larger aggregates, so by differentiation within the magma, and in places especially suitable thereto, heavy-metal compounds originally evenly distributed may segregate to form useful ore-deposits. Such magmatic segregations represent accordingly but portions of rock solidified under special conditions. This case is indicated in Figs. 1 and 2.

(*b*) The water which rising from depth along fissures reaches the surface as hot springs almost without exception contains mineral matter.

If this matter include heavy-metal compounds such as in consequence of particular chemical and physical conditions become precipitated within these fissures, then lodes or metalliferous veins are formed which naturally agree in shape and extension with the fissures. Lodes accordingly are only special cases of fissure filling. This case is illustrated in Fig. 3.

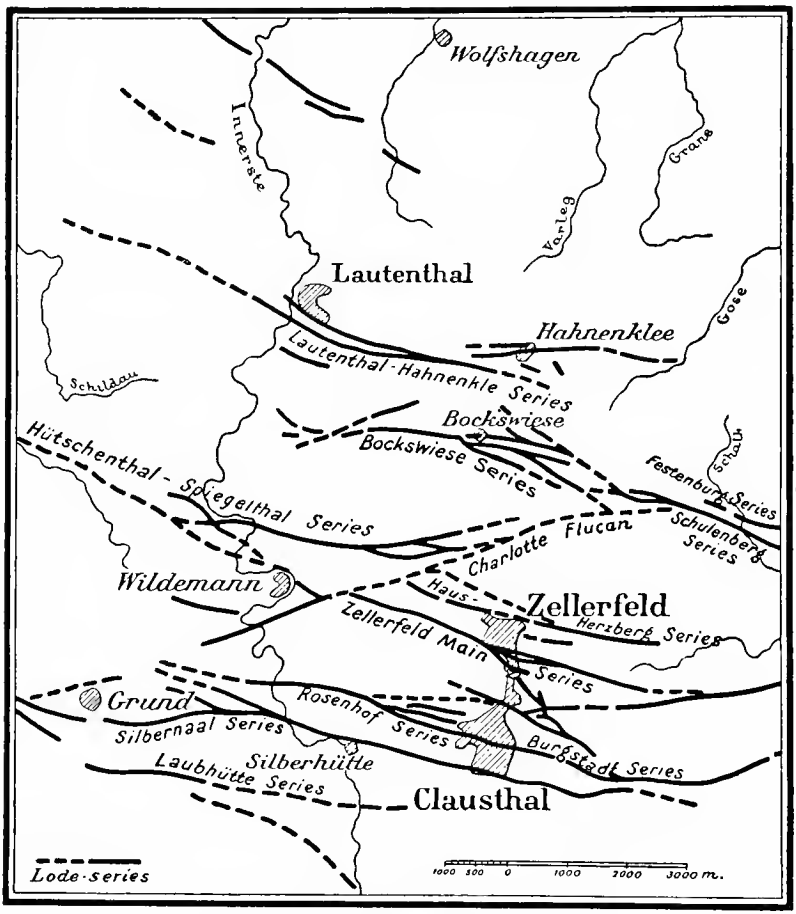


FIG. 3.—The Oberharz metalliferous fissure-system.

(*c*) If sea-water locally contain heavy-metal compounds, then simultaneously with the formation of marine sediments ore may be deposited to such an extent that a metalliferous bed is formed, which in so far as its origin is concerned does not differ essentially from normal sediments. In relation to form both are subject to the same laws, and the ore-deposit represents but a special and chemically-differing section of the otherwise

non-metalliferous deposit. This case is illustrated in Fig. 4.

(*d*) River terraces consist of fragments eroded from the valley slopes and neighbouring plateaus, carried down-stream, and there spread out in regular order. In general they do not contain any useful mineral deposit. Should however the rock eroded have contained for instance a gold or a tin lode, this likewise would have suffered destruction, and its fragments would have been arranged by water among the others in the reaches below, when should the ore content of such fragments be high enough the deposit is termed an ore-gravel. It would differ neither in form nor origin from the ordinary deposit of fragments, and would but represent a portion distinguished by its metal content. This case is illustrated in Fig. 5.

Similarly every deposit brings with it the evidence that it is no independent and separate mass, but that it is very closely related to the geological formations enclosing it. The sum of the relations of an ore-deposit to the country in which it lies constitutes its 'geological position.' The recognition of this important factor is an achievement of the last decade, during which, as will be seen in the special section dealing with the classification of ore-deposits, it has gradually become prominent.

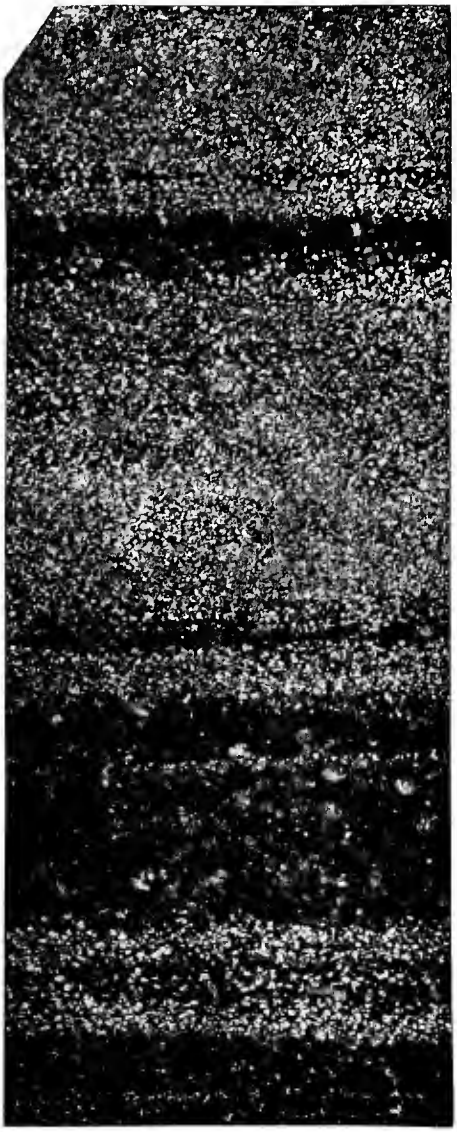


FIG. 4.—Pyritic band from the Witwatersrand, showing pyrite layers, light in colour, with quartzite layers, dark in colour, the composition of these layers differing only quantitatively. Voit, *Zeit. f. prakt. Geol.*, 1908, p. 216.

In addition to the scientific interest which the investigation of the geological position of an ore-deposit offers, it possesses also the greatest technical and economic significance for the miner. Disregard for this

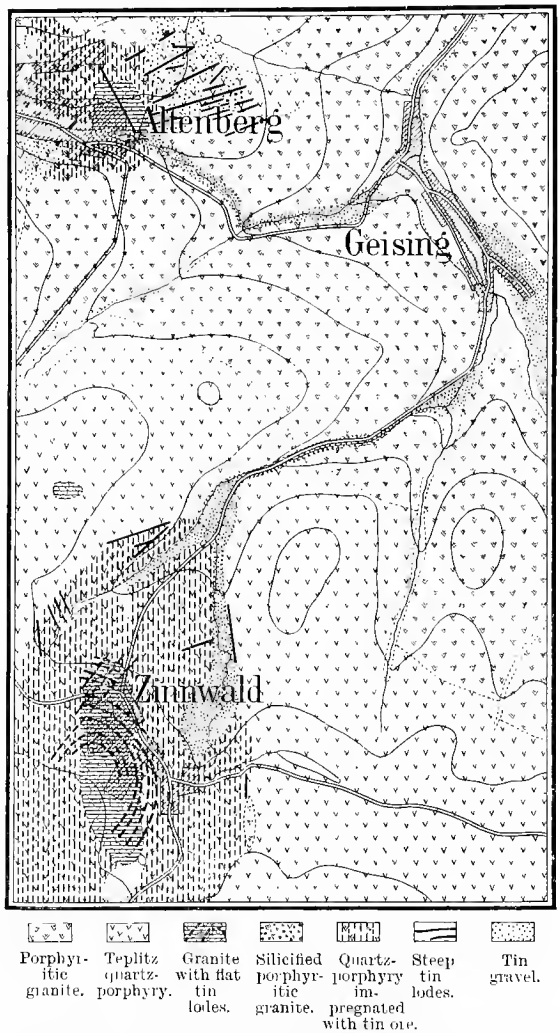


FIG. 5.—The relation of tin gravels to the primary deposits and to the river-system. *Ausschnitt aus der geol. Spezialkarte Sachsens. Sektion Zinnwald.*

factor or, in other words, the adoption of the view that ore-deposits are separate and independent bodies, may lead to great loss to those interested in mining, a possibility rendered apparent by the following examples :

(*a*) Where lode fractures cross a complex in which limestone

alternates with other rocks, the circulating mineral solutions may not only partly dissolve the limestone but may metasomatically transform it into ore. Since such a transformation takes place preferably along the bedding-planes and crevices of the limestone the outlines of the ore-bodies thus arising are extraordinarily irregular and apparently subject to no law.

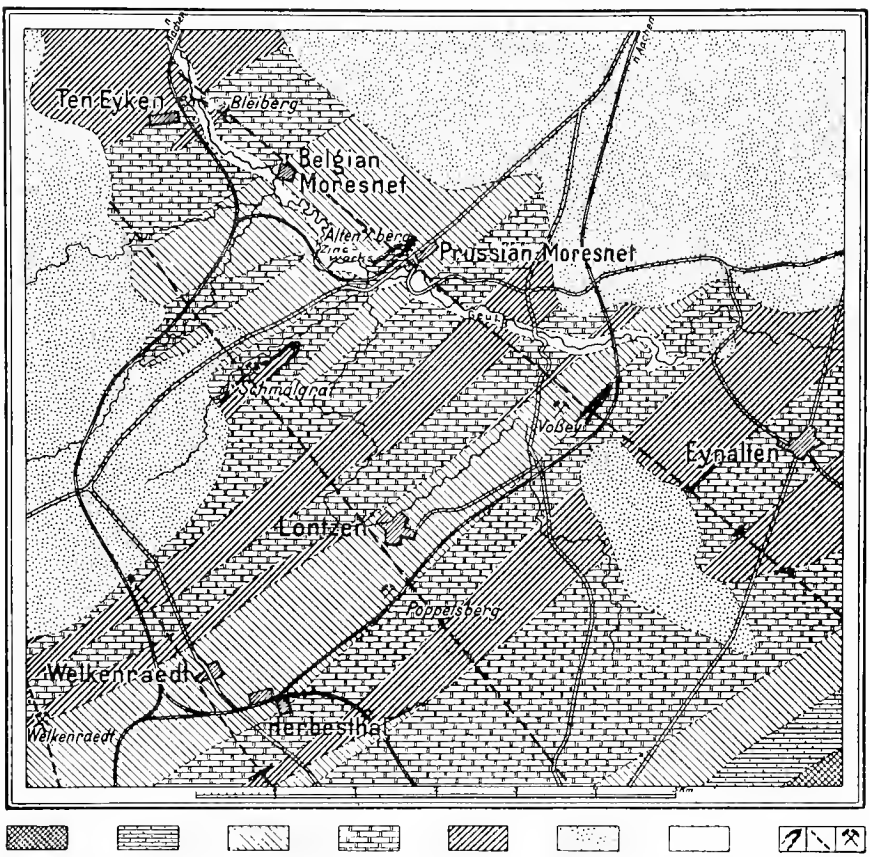
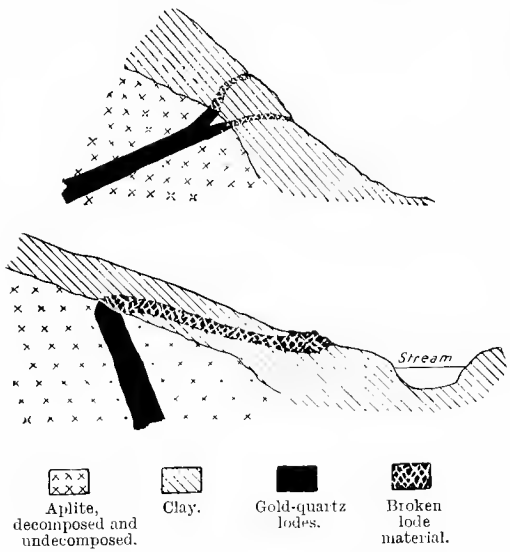


FIG. 6.—The metasomatic lead-zinc deposits around Aachen showing their occurrence at the intersection of limestone and fissures, especially where the limestone is in contact with slate.

As long as such ore-bodies were studied without reference to the country-rock or to their genesis, the discovery of further occurrences was left to chance. As opposed to this, the recognition of geological position and genesis in prospecting and development, causes regard to be paid to the close relationship which exists between the distribution and arrangement of the ore-bodies on the one side and the disturbances which created channels

for the solutions on the other. When investigating such metasomatic deposits the miner schooled in geology will accordingly determine first of all the disposition of the faulting system and of the lines of disturbance, and then the extension of the limestone in which alone the deposits will occur, slate and sandstone not being susceptible to this transformation. With these factors in hand he will look for ore-bodies where fissures and limestone intersect. Further, in placing the boundaries of his mining property he will follow the direction of the principal fissures, and make endeavour to include as much as possible of the easily alterable limestone. Such a geological position is illustrated in Fig. 6.



FIGS. 7, 8.—Gold-quartz lodes at Omai and Anderson's Creek, British Guiana, illustrating the formation of detrital deposits by the drag of the slope. Lungwitz, *Zeit. f. prakt. Geol.*, 1900, p. 216.

(*b*) Another noteworthy example is presented in the case of the auriferous gravel-deposits of British Guiana. Without having studied the geological position of these deposits the experience gained elsewhere was applied to them. In general, rivers transport the gold and concentrate it down-stream. The greatest dimension of these auriferous river deposits therefore usually coincides with the direction of the river. Mining law takes account of this fact in granting claims or concessions, which are narrow in width and have their greatest extent parallel to the river. The same procedure was followed in British Guiana, where, subsequently and to the general surprise, it was found that the length of these deposits was not parallel but transverse to the river. From a more careful study it was found that these alluvial deposits did not belong to the normal type, but resulted from the drag of the detritus down the slope. In consequence of the smaller resistance of the country-rock, the auriferous quartz lodes stood out upon the slope until because of their dip they broke and fell, the pieces descending by the surface drag not only to the river but actually across it. By this manner of formation also the striking fact is explained that the auriferous fragments of these deposits, differing from

those of ordinary river gravels, are fairly angular. In this case the true recognition of the geological situation not only indicated to the gold-washer the proper method of working, but suggested also an alteration in the mining law. This occurrence is illustrated in Fig. 8.

(*c*) In the Lower Devonian complex of Siegerland, consisting of grauwacke and slate, siderite lodes much disturbed in strike and dip

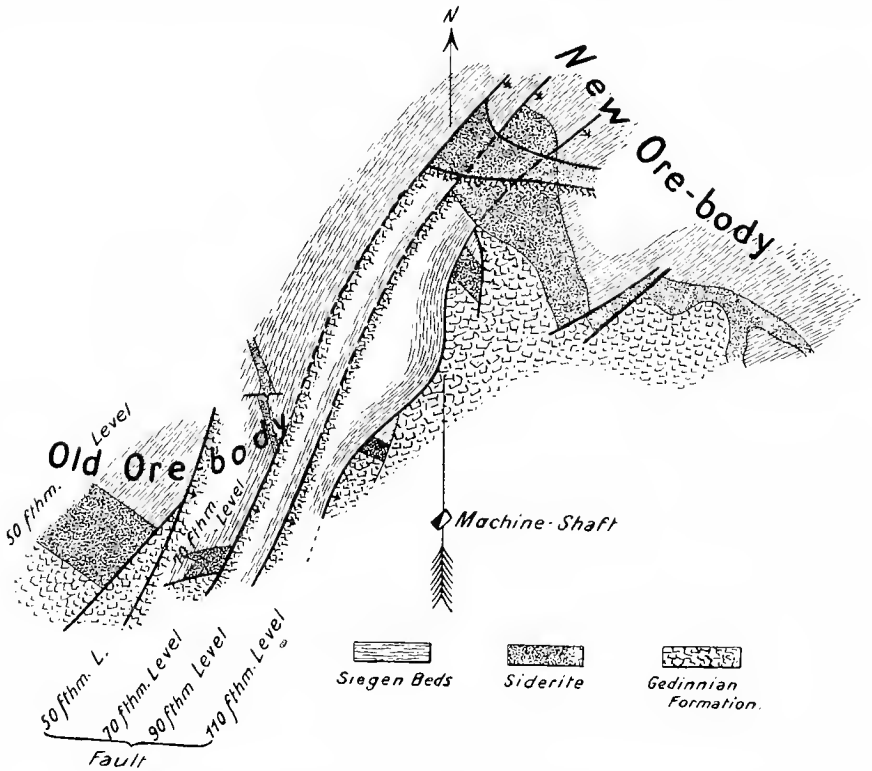


FIG. 9.—The fault at Stahlberg near Müsen, illustrating lateral displacement. Drawing by Von Denckmann.

occur, among which the Stahlbergstock at Müsen is remarkable for its width of from 12 to 27 metres. This lode was noted for its large output till towards the east it was suddenly and completely cut off. At first this disturbance was regarded as an ordinary fault and the continuation was sought mistakenly to the south. When this work met with no success it was supposed that the disturbance was older than the lode itself and that therefore no continuation at all was to be expected. It was only last year that, with the help of the geological survey by

Bornhardt and Denckmann,[1] proof was obtained that a fault occurred along which the rocks in the hanging-wall had sunk at an angle of 45°, whereby the eastward continuation had undergone a considerable displacement to the north. Since the lode occurred at the junction of the Gedinnian and the Siegen formations, the direction of displacement was made manifest by the geological survey of the surface. After proper recognition of this geological position, which is illustrated in Fig. 9, the continuation of the lode was found to the north-east.

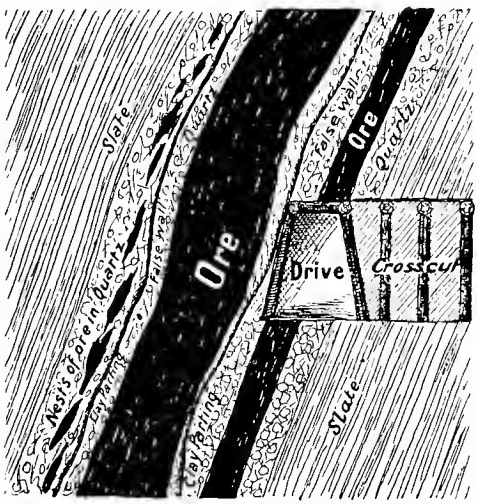


Fig. 10.—False walls formed by the reopening of an already filled fissure.

(*d*) Earth movements may not only cause a displacement at right angles to the strike, but may also bring about a re-opening of an already filled fissure in such a manner that the new fissure approximately coincides in strike and dip with the original lode. Since such fissures within a lode are often filled with clayey material they are not infrequently taken by the miner for lode walls, the boundaries of the lode against the country-rock. In cases of such misunderstanding a portion of the ore-body remains undiscovered. Such false walls are illustrated in Fig. 10.

A knowledge of geological position leads however not only to the discovery of the extension of an ore-occurrence but renders also important service in other directions.

(*a*) A careful investigation of the geological features upon the surface in the neighbourhood of an ore-deposit discloses not only the course of the different geological horizons and their petrographical and chemical-geological properties, but fixes also the geological structure of the country together with the disturbances which may be present. The petrographical properties and the geological structure together render it possible to determine the lay of the ground-water in the district. Since the amount of water in a mine has a great bearing upon mining expenses, the investigation of this ground-water may in certain districts be of great importance. The lead-zinc lodes at Velbert south of the Westphalian coalfield represent the prolongation to the south-east of the transverse disturbances of the Lower

[1] *Zeit. d. D. Geol. Ges.*, 1906, Protocol, p. 93.

Rhine-Westphalian Coal-measures, which formation in part is notorious for the water encountered in it. These lodes cross certain rivers from which they appear in part to take the water, the flow in some of the mines of this district having been so considerable as to have led to the eventual stoppage of almost all work. This geological position is illustrated in Fig. 11.

(*b*) Examination of steeply-inclined deposits has shown that with many metals a change in the fairly even distribution of original deposition

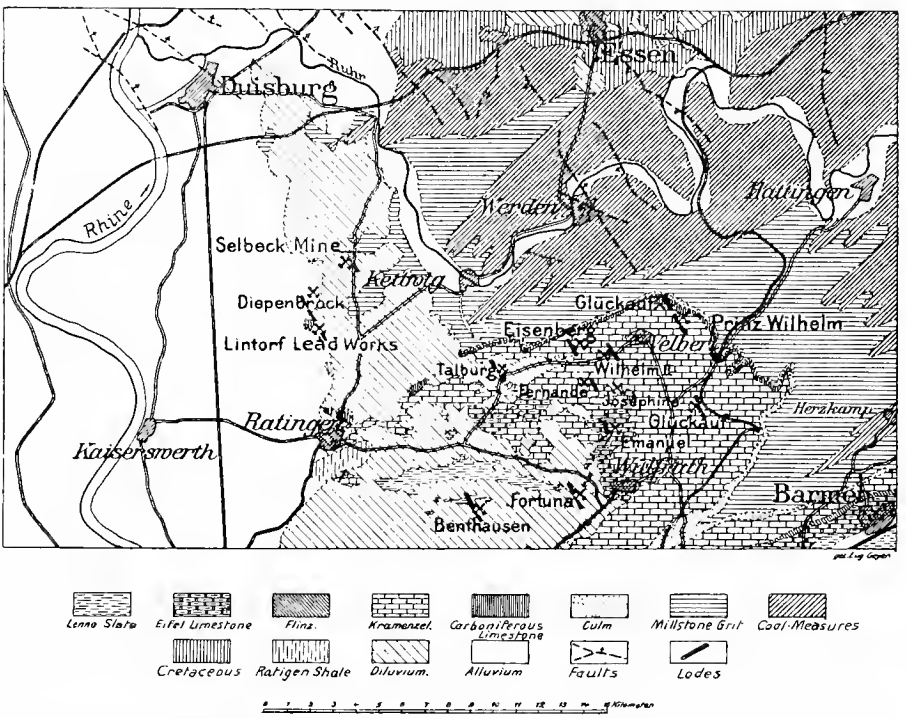


FIG. 11.—The Velbert district south of the Westphalian coalfield, showing the connection between ore-deposits and faults, the ore-deposits in this case representing the continuation of the faults of that coalfield.

may gradually be brought about entirely by the action of the atmosphere; such a migration results in what may be termed 'secondary depth-zones.' The upper portion of a lode to a certain depth may thereby be robbed of practically all its heavy metals with the exception of iron, the amount of which becomes increased. This zone is termed the 'gossan.'[1] The heavy metals previously present are removed in solution to a deeper horizon where, after exhaustion of the solvent and of the oxygen carried down by atmospheric water, they become precipitated by the primary

[1] *Eiserner Hut.*

sulphides there present. In this manner, under the 'oxidation zone,' a zone of 'secondary enrichment' or 'cementation' is formed, which within a very small vertical measurement often contains almost all the metal formerly evenly distributed over a depth of hundreds of metres which have slowly succumbed to the forces of erosion. Below this zone again comes the 'primary zone,' the metal content of which is generally out of all proportion lower than that of the cementation zone. This sequence of zones is illustrated in Fig. 12.

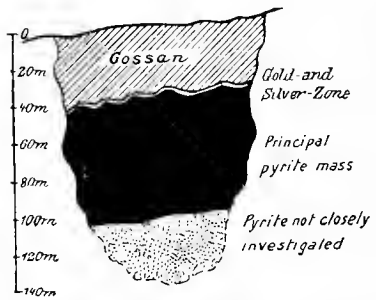


FIG. 12.—Vertical section of No. 2 ore-body, Rio Tinto, illustrating secondary depth-zones in the case of cupriferous pyrite carrying a little gold and silver. Vogt, *Zeit. f. prakt. Geol.*, 1889, p. 250.

Since the processes of decomposition and migration which result in the formation of the gossan and the cementation zone in a complete section may reach to the ground-water level, not only is an impoverishment of the deposit there encountered but water difficulties also begin. Early prospecting and development work usually takes place above the water-level, that is to say in the oxidation and cementation zones when these are present. Under these circumstances should the mining engineer not fully appreciate the effect of secondary variation in depth he is in danger of applying, as often happens, the high content of the enriched zone, which at best will only hold to water-level, to a greater depth, obtaining thereby an entirely false conception of the deposit concerned. Since in many cases minerals appear in the cementation zone which are characteristic of that zone, a careful study of the minerals in any occurrence should protect the mining engineer from such a false conception.

The proper understanding of the geological position brings forward therefore a number of points which allow an individual consideration of each separate ore-occurrence. The modern methods of investigation consequently avoid the inclination to generalize, which is so damaging to mining, and to which those especially are prone whose opinion, in consequence of an experience gained in only one district, is one-sided. The statement that all ore-deposits become poorer from the surface is just as little justified as one to the contrary. Such generalizations which might well bring whole mining districts into discredit would be impossible if each deposit were regarded as the function of its special geological position and genesis. Naturally, in addition to these two factors, both shape and content must receive the same attention as they did when deposits were regarded in the old light. Only after the consideration of all four of these factors is

a proper understanding of an ore-occurrence possible, and only then do the data necessary to the determination of the best system of working appear. In the investigation of deposits therefore the circumstances relating to genesis and deposition are given first place, shape and content at the same time receiving due consideration. In prospecting, a proper understanding of the geological position and genesis makes it possible not only to follow an ore-occurrence but also to discover other similar deposits, while the determination of shape and content is necessary for the estimation of quantities, as well as for fixing the proper methods to employ in development, mining, and treatment.

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(*c*) General Maps of Ore-Deposits

Germany. Karte der nutzbaren Lagerstätten Deutschlands. Berlin.—France. Carte minéralogique de la France.—Austria and Hungary. Karte der Verbreitung nutzbarer Mineralien in der Österreich-Ungarischen Monarchie nebst Bosnien und Herzegowina.—Hungary. Karte der nutzbaren Mineralien Ungarns.—Russia. Carte des gites minières de la Russie d'Europe.—East Africa. Karte der nutzbaren Lagerstätten. Berlin.

CLASSIFICATION, FORM, AND GRAPHIC REPRESENTATION OF ORE-DEPOSITS

DEPOSITS are divided into syngenetic and epigenetic deposits according to their relation to the country-rock.

Syngenetic deposits have the same origin as the country-rock with which generally they are contemporaneous. They may be either of sedimentary formation, in which case they are distinguished by their conformity; or they may be eruptive and then dependent upon the solidifying rock from which they have resulted. There are accordingly two principal groups of syngenetic deposits, namely:

1. Magmatic segregations.
2. Sedimentary ore-beds. From this group, from long usage rather than upon any real ground, a third is generally made, namely:
3. Gravel-deposits.

Epigenetic deposits are younger than the country-rock, of which in general they are independent, and with which they are not usually conformable. Such deposits may be divided into four groups, namely:

1. Contact-metamorphic deposits.
2. Cavity-fillings.
3. Metasomatic deposits.
4. Impregnations.

Although with all these groups form may in general be only of relatively small significance in the investigation of genesis, it remains however an extremely important factor in prospecting, mining, and treatment. Admittedly a number of deposits of widely different genesis may often have the same form, as for instance contact-metamorphic and metasomatic occurrences, bedded lodes and steep ore-beds, pisolitic or oolitic ores and fragmentary deposits, yet in spite of this the form of a deposit is in general a function of its genesis. Thus magmatic segregations are generally irregular, while sediments, in harmony with deposition from still water,

generally exhibit regular form; with lodes and cavity-fillings the form of the ore-body is dependent upon that of the pre-existing cavity; with metasomatic deposits upon the chemical property and the extension of the country-rock; and with impregnations upon permeability to water, mineral solutions, magmas, or gases.

I. Form of the Syngenetic Deposits

(*a*) *Magmatic Segregations.*

Under magmatic deposits is understood those occurrences which owe their origin to separation within a molten magma, that is to magmatic differentiation. Just as here and there larger masses of mica or felspar may separate out of a granite magma so also may ores, such for instance as magnetite, ilmenite, chromite, and pyrrhotite, separate themselves from those eruptive rocks which ordinarily contain them as accessory or secondary constituents. Such a genesis, which is illustrated in Fig. 13, brings with it great variety in form and usually an indefinite outline. The segregated mass may be either very small as in the case of the diamond and of platinum, or it may be large as with the less valuable compounds of iron, nickel, copper, etc. The ore-bodies are sometimes irregularly distributed within the consolidated rock, in which case they are characterized by a gradual passage at their borders from ore to normal rock; sometimes, as illustrated in Fig. 14, they occur at the contact of the eruptive mass with the country-rock; or, as illustrated in Fig. 16, they sometimes penetrate the country-rock in a manner similar to dykes. Their form is therefore in the highest degree variable and affords little which may be regarded as characteristic. Concentrated in this manner are found the diamond; some native metals as platinum and nickel-iron; oxidized ores such as chromite, titaniferous magnetite, ilmenite, magnetite, and specularite; and sulphide ores such as nickeliferous pyrrhotite, chalcopyrite, and pyrite. With every such deposit the great

Fig. 13.—Magmatic deposits within an eruptive mass. Chromite in peridotite. Hestmando in Norway. Vogt, *Zeit. f. prakt. Geol.*, 1894, p. 391.

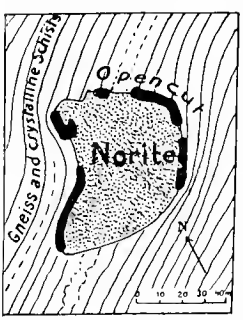


Fig. 14.—Magmatic deposits at the periphery of an eruptive mass. Meinkjär nickel-pyrrhotite mine, Bamle, Norway. Vogt, *Zeit. f. prakt. Geol.*, 1893, Plate VI.

irregularity in form compels the most complete development before any reliable estimate of quantity may be made. Concerning size, some Scandinavian iron deposits of this genesis, as for instance those at Kiirunavaara and Luossavaara, contain tremendous quantities, and some of the Canadian nickel-pyrrhotite deposits have equally large dimensions. Often, however, small but numerous aggregates are collected near one another, yet presenting on account of their irregular distribution and variation in size great difficulty to prospecting, mining, and treatment.

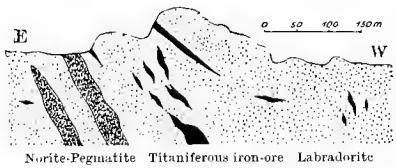


FIG. 15.—Magmatic deposits within an eruptive mass. Blaafjeld near Soggendal, Norway. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 7.

(*b*) *Sediments or Ore-Beds.*

The formation of ore-beds takes place either by the mechanical accumulation of pre-existing ore, or by chemical precipitation chiefly in still water. The occurrences which belong to this group are formed therefore in the same manner as the other layers with which they are conformably bedded, and under normal conditions the old mining definition holds good, that they are deposits which are younger than the beds in the foot-wall and older than those in the hanging-wall. Ore-beds, as illustrated in Fig. 17, have therefore a very simple tabular form, though as they are but exceptional cases of ordinary sediments they are generally of somewhat limited dimensions, that is they usually give out in all directions and possess therefore in general a lenticular form. Moreover it is not often that they are regular in composition or consist entirely of ore, more generally rock and ore alternate. It also often happens that at the consolidation of the material and while it was still soft, a concentration of the originally evenly distributed mineral occurred in places particularly suited thereto, whereby a layer became formed very similar to an impregnated zone. In other cases ore-beds, the so-called detrital deposits, have been formed by the concentration and consolidation of fragments of older occurrences. Thus beds of limonite are found in the Senonian of the Chalk formation at Peine, the material of which, as indicated by the *Ammonites* found in the boulders, was derived from the Gault.

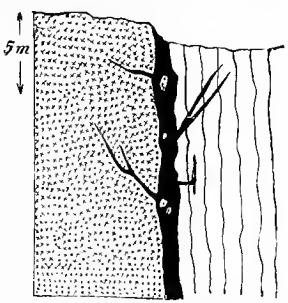


FIG. 16.—Magmatic pyritic deposit occurring at the contact of norite and gneiss. Erteli nickel-pyrrhotite mine, Norway. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 136.

There is no general law applicable to the extension of these deposits. Gigantic occurrences are known, such for instance as the Cleveland, the

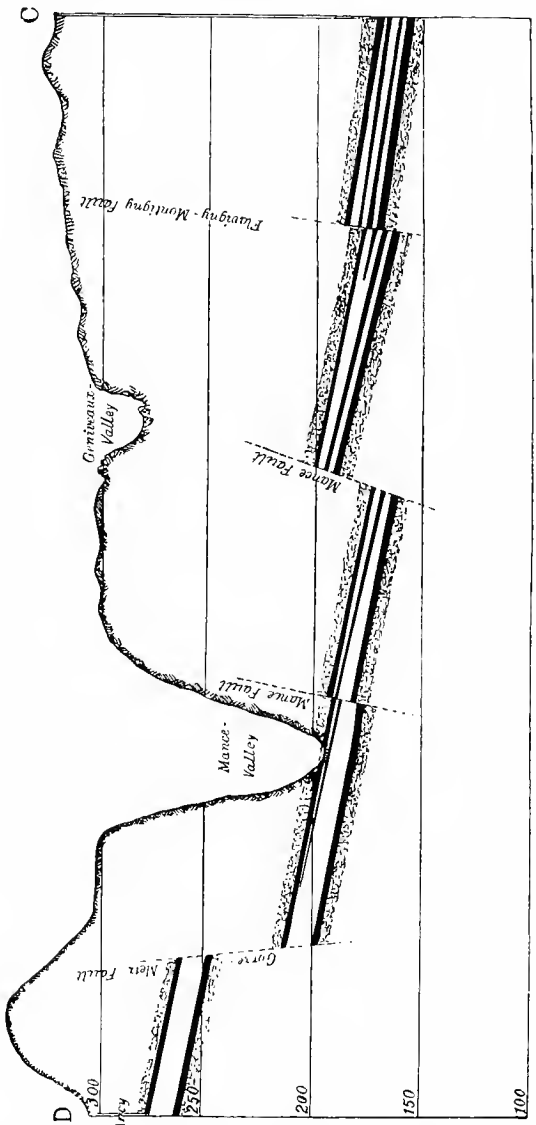


FIG. 17.—Section through the Minette district north of Gorze showing the disposition of the ore-beds and their passage along the strike to normal sediments. In the drawing the ore-beds are black while the beds of marl are dotted. The vertical scale is ten times that of the horizontal. Ansel, *Zeit. f. prakt. Geol.*, 1901, p. 87.

Minette, and the Clinton deposits, which cover many square kilometres and even cross the boundaries of large government departments; on the other hand there are some so small that they must be described as nests.

In all cases however these deposits undoubtedly possess considerable economic advantages over those of other groups, not only in the regularity of their occurrence both in strike and dip but also in the homogeneity of their composition. Moreover since in consequence of this regularity their ore-reserves may be estimated without any great difficulty, they are comparatively simple to value and also easy to mine.

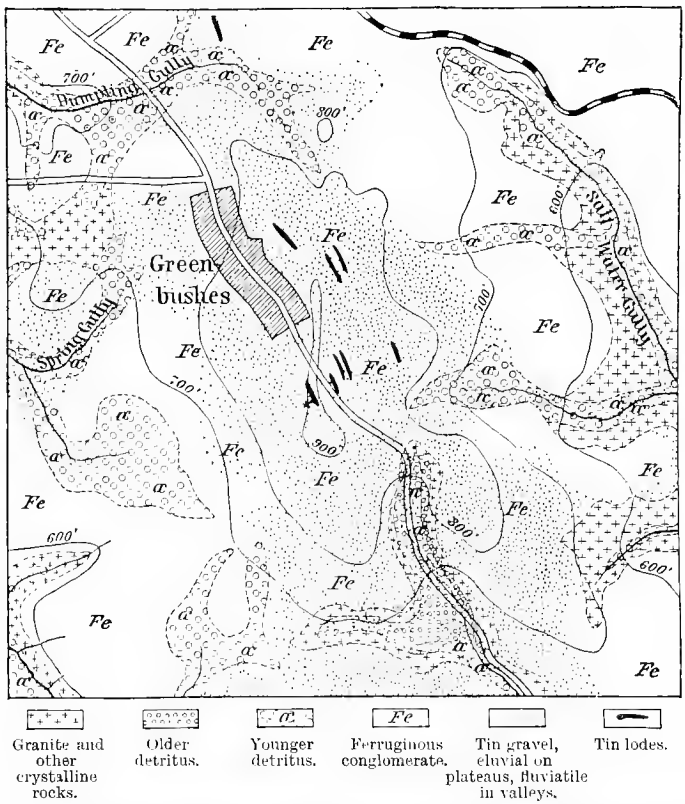


FIG. 18.—Distribution of eluvial and fluviatile tin gravels in relation to the primary deposits. Greenbushes, Western Australia. Krusch, *Zeit. f. prakt. Geol.*, 1903, p. 379.

(c) *Gravel-Deposits.*

Since gravel-deposits also are consequent upon the disintegration of deposits previously existing there is in reality no difference based on the general principles of genesis between these and ore-beds. The difference consists entirely in the fact that the latter, in consequence of their greater geological age, have become consolidated and covered with younger beds while the gravel-deposits, generally only of Quaternary or

at the earliest of Tertiary age, remain in greater part loose surface formations.

According to their formation the fluviatile and the marine gravel-deposits must be distinguished from the eluvial. The material of the former has been arranged in position either by river action or by that of the sea, during which arrangement a slight chemical enrichment has often taken place. On the other hand the eluvial deposits are consequent upon the disintegration of primary deposits chiefly in places where, though downpours were rare, the lighter particles became removed by occasional rain and wind, leaving those heavier to settle down and form gradually an ore-deposit practically *in situ*. More often however both classes of gravel-deposits are found in close proximity, the eluvial upon the plateaus and slopes and the fluviatile occupying the immediate and proximate river courses. This position is illustrated in Fig. 18.

Disturbances of the Syngenetic Deposits

By disturbances of the syngenetic deposits is meant the numerous changes in stratigraphy and displacements in space which these deposits have suffered since their formation. These are known under the terms 'folding,' 'overthrusting,' 'faulting,' 'vertical displacement,' and 'horizontal displacement.'

1. *Folding or Plication.*

When horizontal pressure acts upon a complex of beds it causes these to become folded into 'anticlines' and 'synclines' with flanks or limbs so much the steeper as the pressure was the more intense. Since syngenetic deposits wherever they occur in the Geological Record are but members of special chemical composition, they have suffered all the changes to which the whole complex was subject, though this is naturally more strikingly the case with the tabular sediments than with the magmatic segregations.

q, Quartzose bedded mass containing antimony ore; *k*, Limestone; *s*, Clay-slate; *t*, Trachyte.

Fig. 19.—Simple anticline and syncline. Bedded stibnite deposit between limestone and clay-slate near an occurrence of trachyte, near Kostainik, Servia. Beck, *Zeit. f. prakt. Geol.*, 1900, p. 35.

The transverse section of an anticline and syncline is sometimes gently undulating as illustrated in Fig. 19, and sometimes, as when the pressure is more intense, zigzag as illustrated in Fig. 22. In horizontal section anticlines and synclines appear either with the closed outline of a more or

less perfect ellipse as illustrated in Fig. 20, or they extend in one particular direction presenting then the picture of an undulating line winding more or less markedly across the line of average strike, the undulations on

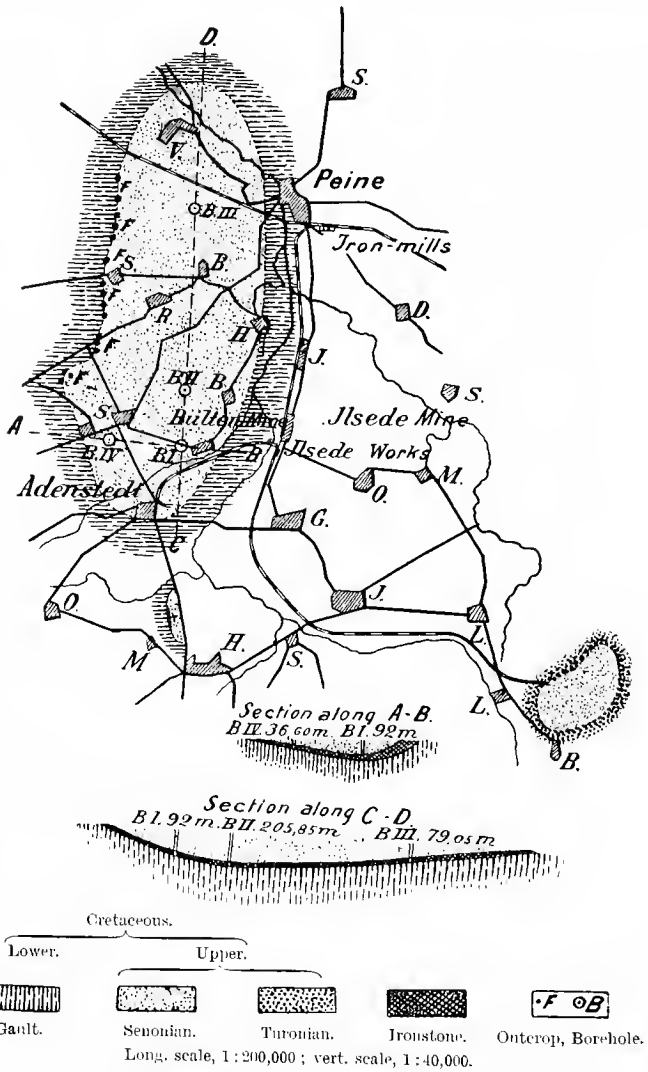


FIG. 20.—The ironstone bed at Peine. Plan and section of a closed syncline.

one side representing the anticlines, those on the other the synclines. Such a horizontal section is shown in Fig. 21.

The line which unites the deepest points of a syncline is known as the

'synclinal axis'; similarly that which is formed by joining the highest points of an anticline is termed the 'anticlinal axis.' These axes, in consequence of the dip of the flanks, are usually found occupying a central position along a line which must be approximately at right angles to the direction of the pressure. The courses of these axes are especially important, since they are but rarely the simple horizontal line of a closed syncline or the simple inclined line of an open one. Far more often they are bent and re-bent to conform with the smaller anticlines and synclines which build up the larger occurrences. This formation of smaller members is not only found along the axes but occurs also at right angles to them. It is not always the case that the anticlinal or synclinal flanks are even planes with regular dip; generally the process of folding has so worked that each syncline shows in its transverse section a number of secondary anticlines and each anticline a number of secondary synclines.

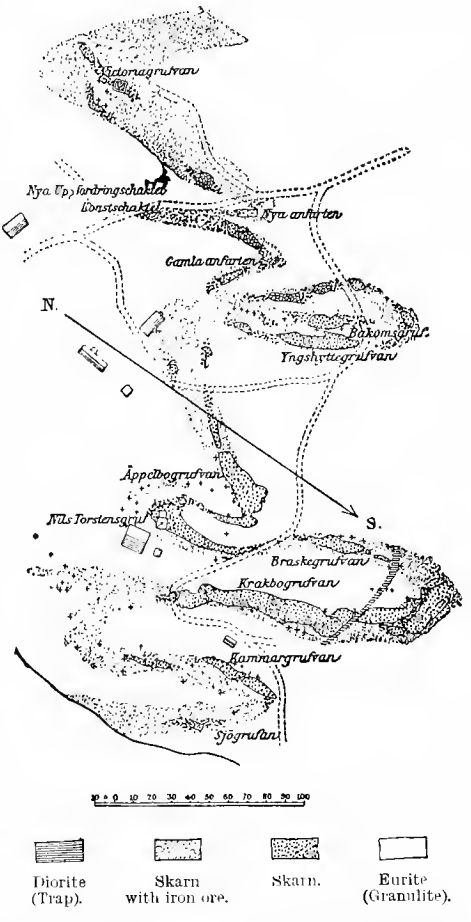


FIG. 21.—General map of the contorted bedded iron ore-deposits in the Högberg district near Persberg, Sweden. W. Petersson, *Zeit. f. prakt. Geol.*, 1899, p. 5.

The anticlines and synclines produced by folding are expressed upon the surface as differences in level, which differences, disintegration, and erosion are ever working to remove. The crests of the anticlines are the first to go, and then along the central ridge older beds appear flanked on either side by successively younger beds. The portion of the anticline thus removed is known as the 'air-anticline.' In the first stage of folding the two flanks of anticline and syncline incline towards one another as illustrated in Fig. 19. With more intense folding it often happens that they are overturned both then inclining in the same direction

as illustrated in Fig. 22; the Rammelsberg deposit at Goslar for instance lies in such an overturned anticline. While with normal folding each bed

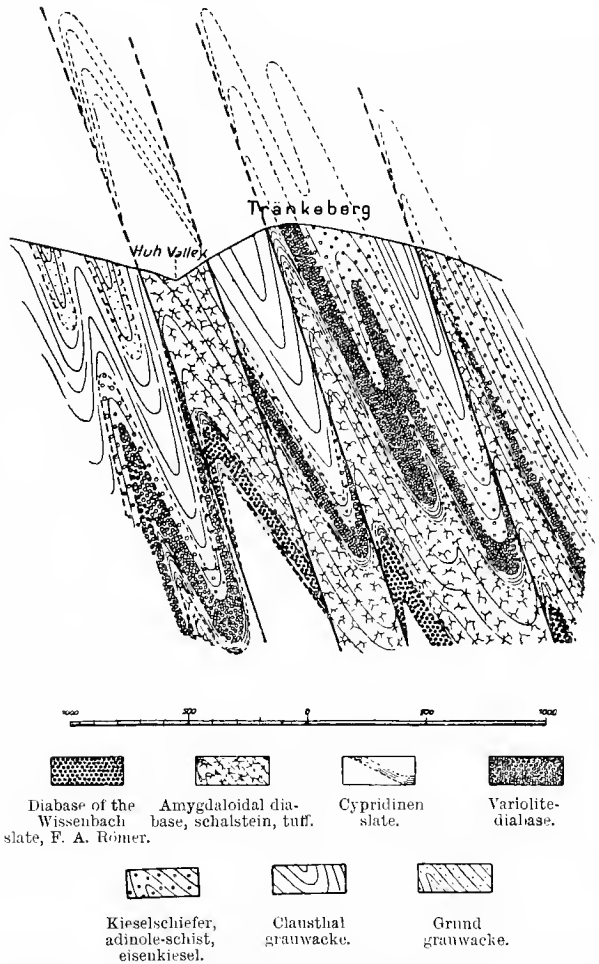


FIG. 22.—Steep overturned anticlines, air-saddles and overthrusts. Section of the Oberharz diabase-belt by M. Koch. The limestone and ironstone of the Stringocephalus beds occur between the Cypridinen slates and the diabases.

is followed in the hanging-wall by one which is younger, with overturned beds the reverse is the case. The more intense the folding the closer are the limbs of anticline and syncline brought together.

2. *Overthrusting.*

Should in folding the limit of elasticity be passed a fracture of the beds takes place in consequence of the extreme strain to which one of the synclinal limbs is subjected; then along this fracture, as a further effect of folding, older beds are thrust over younger beds in the direction of the pressure. Such dislocations which are especially connected with anticlines, are called 'fold-faults' or 'overthrusts.' Their formation is illustrated in Fig. 23. In their neighbourhood and in consequence of the manner in which they were formed, the beds concerned are drawn out and have not their normal thickness. It is also characteristic of this form of disturbance that seldom does a simple fissure result but generally a whole group, and a zone of disturbance arises which may in cases have a width of 500 m.

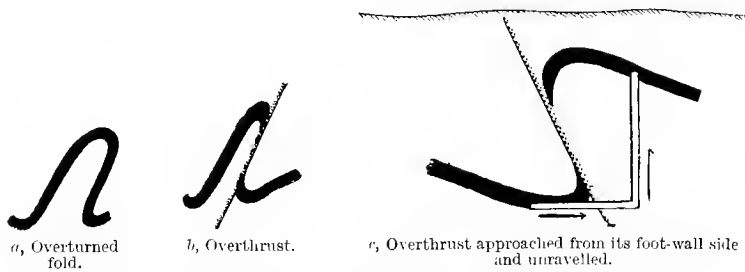


FIG. 23.—*a* and *b* represent diagrammatically the phenomenon of overthrusting; *c* illustrates the unravelling of an overthrust.

or more. These disturbed zones, one of which is illustrated in Fig. 24, consist in general of rock material most intensely contorted and crushed, in which larger fragments of the neighbouring beds and perhaps also of an ore-deposit occur irregularly bedded. They are generally crossed in all directions by narrow veins filled with secondary minerals.

In consequence of the fact that an overthrust is the end result of intense plication there is often no sharp boundary between the disturbed zone along which the thrust has taken place and the beds whose structure has remained undisturbed, but generally, and especially in the hanging-wall of the thrust-plane, there occurs a gradual passage from the crushed material to the condition of normal deposition. It is also characteristic of this form of dislocation that in the hanging-wall of the disturbed zone the beds are older than those immediately opposite to them in the foot-wall. While however in the case of overturned folds the beds follow one another in unbroken sequence, even though this be reversed, in the case of an overthrust and in consequence of the upthrow of the older beds, the disturbed zone causes a break in the sequence in that when driving into the foot-wall

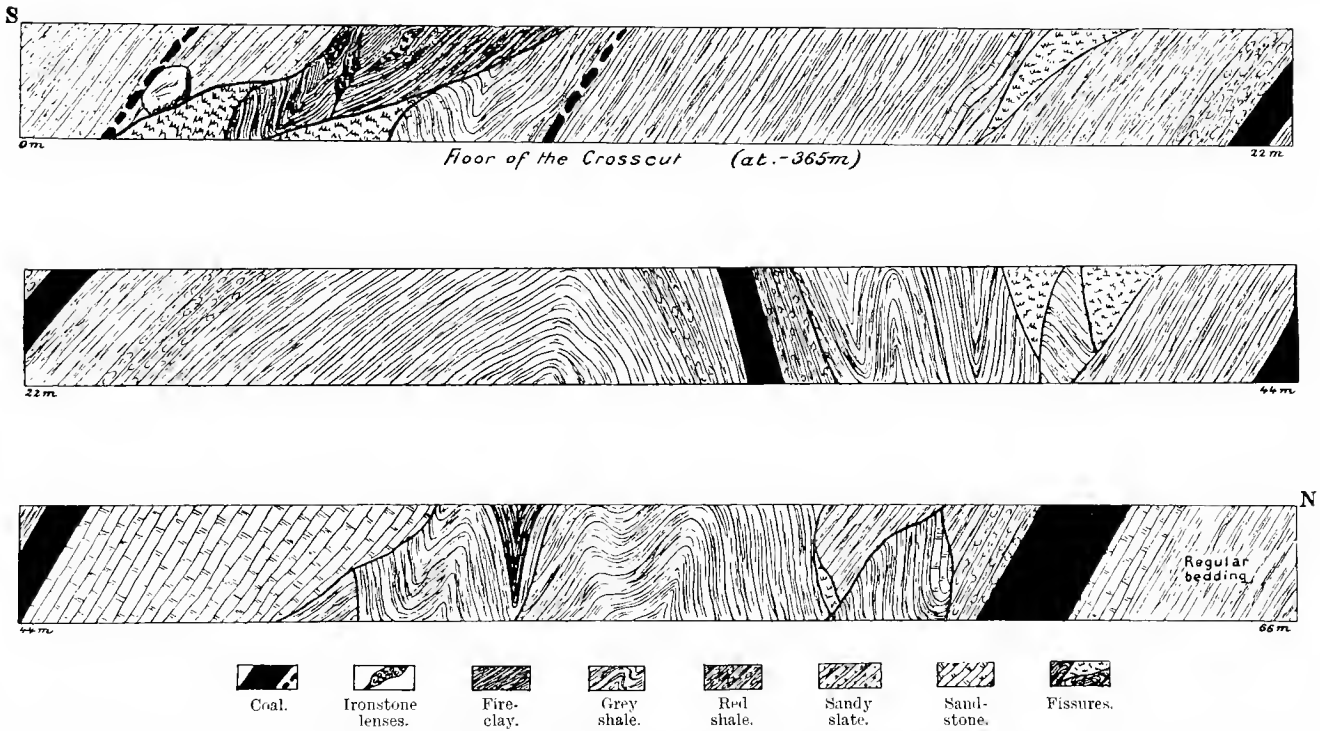
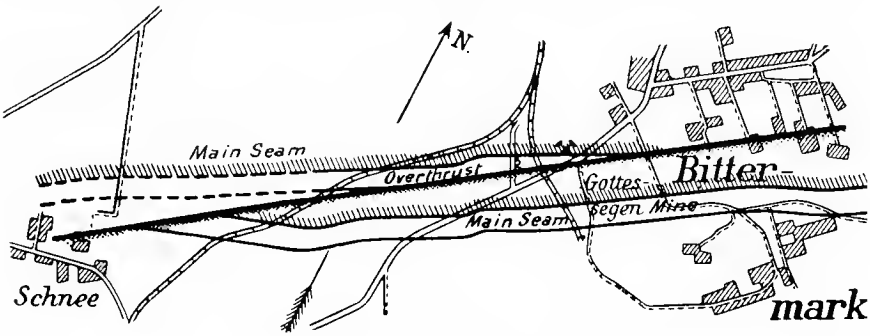
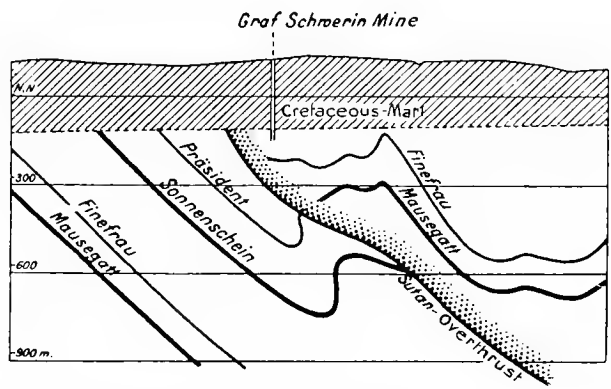


FIG. 24.—The 'Sutan' overthrust in the Zentrum mine. Krusch, *Erläuterung zu Blatt Dortmund.*

successively older beds are met, while towards the hanging-wall the beds are successively younger. In the unravelling of the problems caused by such overthrusts the drag of the beds to the thrust-plane, illustrated in Fig. 23, gives the miner the direction in which he should seek for the severed and displaced portion of the deposit. Zimmermann's rule however, given



a, Plan.



b, Section.

FIG. 25.—(*a*) Plan of an overthrust in the Gottessegen mine near Löttringhausen. Krusch, *Erläuterungen zu Blatt Witten*. (*b*) Section showing the 'Sutan' overthrust in the Graf Schwerin mine. Krusch, *Erläuterung zu Blatt Dortmund*.

on p. 30, does not hold good in these cases but the reverse reading of that rule. From the direction of this drag it may be determined from which side the disturbance is being approached, that is whether from the moved or unmoved side. In the unmoved portion the drag of the beds to the thrust-plane is directed upwards, while in the displaced portion it is downwards. If therefore the overthrust is approached from the unmoved side either a rise is made in the material of the disturbed zone—a procedure which in consequence of the weakness of the rock often presents great difficulty—

or the drive is continued horizontally through that zone and the continuation of the deposit is then sought upwards in the hanging-wall of the thrust-plane. If on the other hand the overthrust is approached from the displaced portion then either the zone itself is followed downwards or it is penetrated horizontally and the unmoved terminal of the deposit is sought downwards in the foot-wall. Should, when seeking within the disturbance for the faulted portion, detached pieces of the ore-deposit be found, these may be regarded as certain evidence that the search is being prosecuted in the right direction.

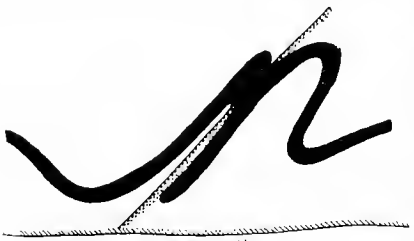


Fig. 26.—Section.

Fig. 27.—Plan.

Figs. 26, 27.—Section and plan illustrating the doubling of width by an overthrust.

In plan, as illustrated in Fig. 25, an overthrust has the appearance of an anticline, one limb of which has been completely squeezed out, its place being taken by the disturbed zone which runs almost parallel to the strike of the country. In consequence any deposit there occurring would in plan appear duplicated. In such cases if the intervening width becomes less and less until finally it disappears, the two portions of the deposit come together and the width of the body becomes doubled. This case is illustrated in Figs. 26 and 27.

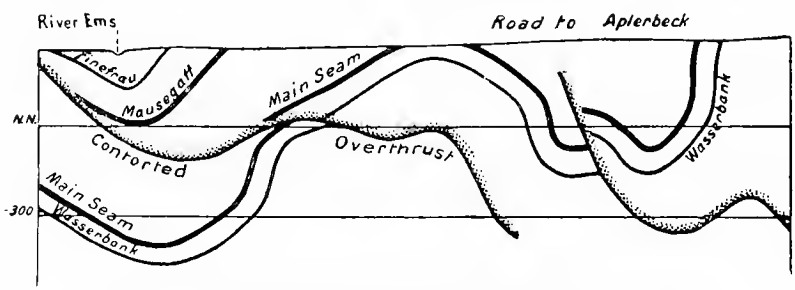


Fig. 28.—Contorted overthrust in the Bickefeld mine near Aplerbeck. Krusch, *Erläuterung zu Blatt Hörde.*

In many cases overthrusts were already present at a time when folding still continued to develop. Then, as was proved by Cremer by an extremely interesting case in the Westphalian coalfield,[1] these overthrusts also become folded. Since however they generally dip more steeply than the beds, they cut through these latter, forming more undulating anticlines and

[1] Glückauf, 1894. Nos 62-65.

synclines than these, but following them so far as their steeper dip permitted. Such an occurrence is illustrated in Fig. 28.

The extent to which beds are displaced by overthrusts varies considerably. On the one hand, even though a wide zone of disturbance occur, the displacement may amount to only a few centimetres, while on the other it may amount to many hundreds of metres. Since overthrusts result from extreme plication they cannot occur in rock complexes which are undisturbed or lie horizontally; moreover it is not always that the nature of a bed will allow it to bend. In such cases folding does not occur but a shattered zone following more or less the strike of the country results, which zone often subsequently becomes mineralized by solutions entering through the numerous resultant fractures.

The direction in which a thrust-plane dips is towards the pressure which produced it; more rarely it happens that, in consequence of resistance offered by particular beds, an opposing pressure and at the same time an opposite overthrust became produced. In transverse section then, two divergently-dipping overthrusts appear, between which a large section of the deposit remains in its original position, though on either side it has been upthrown. Such an occurrence is illustrated in Fig. 29.

FIG. 29.—Two overthrusts dipping away from one another, the portion of deposit between them remaining unmoved at a lower level.

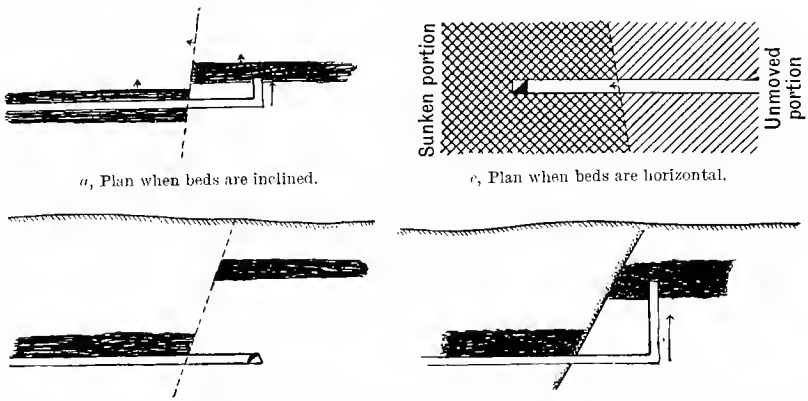
3. *Faulting.*

Normal faulting occurs when, after fracturing, the rocks in the hanging-wall sink to a lower level. According as the fracture is more or less complete so do these rocks follow exclusively the attraction of gravity by sinking vertically, as illustrated in Figs. 30, 31, and 32, or they suffer in sinking a certain amount of turning around some point along the continuation of the fracture where the two portions of the beds still hold together. It also often occurs that at the fault the beds have become turned or dragged in the direction of the faulted portion in the manner illustrated in Fig. 33.

To know exactly the behaviour of a fault at all points along its strike is only possible where underground workings have completely disclosed the occurrence. This is for instance the case with some of the cobalt lodes at Schweina which cause a sinking of the *Kupferschiefer* amounting at the most to 10 m. When driving on such a lode it may be seen how at one point the *Kupferschiefer* gradually and without transverse break sinks, till the displacement, at a point approximately half-way along the lode, reaches

the above-mentioned maximum. Beyond this again the sunken portion gradually rises till it once more unites, completely and without transverse break, with the unmoved portion. This faulting, which is illustrated in Figs. 32 and 34, resembles therefore the sinking of a piece of cloth stretched horizontally and cut in the middle, when one edge of the cut is weighted.

It lies in the nature of faulting that faults must be younger than the beds in which they occur and older than any movement which may have



a, Plan when beds are inclined. *c*, Plan when beds are horizontal.

b, Section when beds are inclined. *d*, Section when beds are horizontal.

FIG. 30.—Diagrams illustrating the application of Zimmermann's rule for the unravelling of a fault when this is approached from its hanging-wall side.

Section when the beds are horizontal.

FIG. 31.—Diagram illustrating the application of Zimmerman's rule when the fault is approached from its foot-wall side.

taken place along them. The direction in which faults traverse rock-complexes varies considerably though it is the case that they often cross more or less at right angles. In most cases, on account of some obliqueness of this angle, of the inclination of the beds, or of the sometimes incomplete separation along the fracture, there occurs in addition to the sinking of the beds a lateral displacement so directed that the two separated portions remain in plan practically parallel. While in transverse section normal faulting presents the simple picture of a sunken mass, as illustrated in Figs. 30 and 31, in plan it is this lateral displacement which as illustrated in Fig. 35 receives pronounced expression.

Faults very seldom occur alone but in plicated as well as in level-lying country they generally occur in groups or systems. In plicated districts

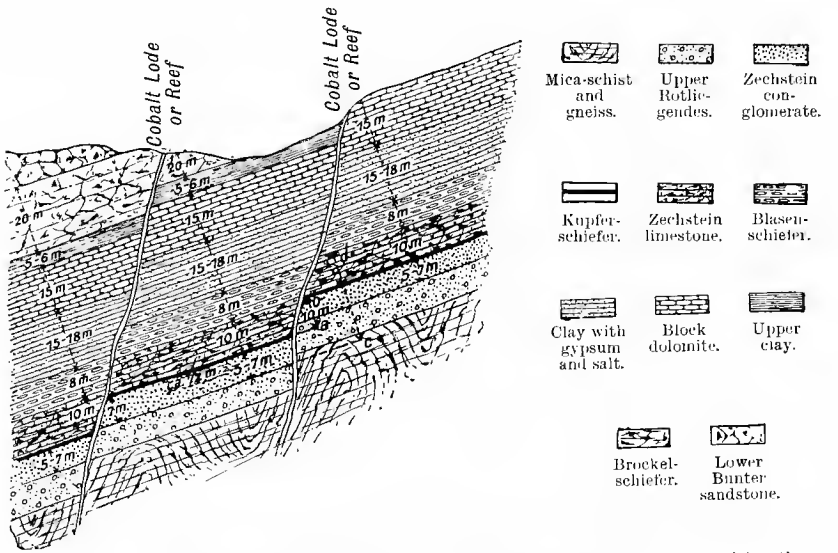


FIG. 32.—Faults in the Zechstein formation. The cobalt lodes of Schweina faulting the *Kupferschiefer*. Beyschlag, *Zeit. f. prakt. Geol.*, 1898, p. 3.

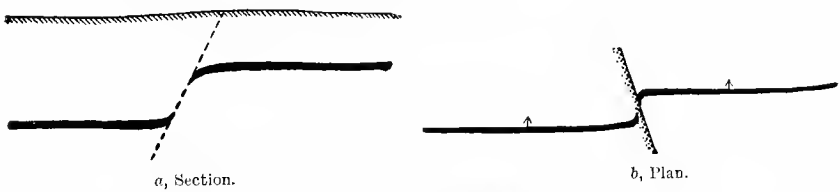


FIG. 33.—Drag of beds at a fault.

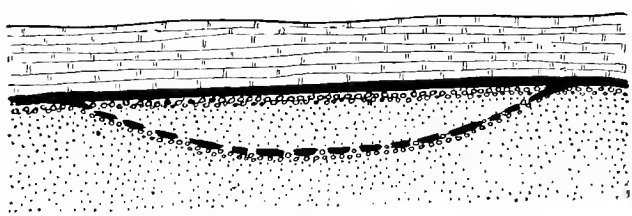


FIG. 34.—Diagram of the displacement of the *Kupferschiefer* by the cobalt lodes of Schweina. The sunken portion is projected in a dotted line and the unmoved portion in a strong line upon the plane of a cobalt lode.

they usually cross the beds more or less at right angles, and, in so far as the movement along them is concerned, are younger than any overthrusts

which may be present. The reason for this relative age is probably because though the transverse fissures arose when folding took place, gravity could not come fully into play to produce displacement till the horizontal pressure causing folding and overthrusting had come to an end.

The members of a system of contemporaneous faults are often parallel,

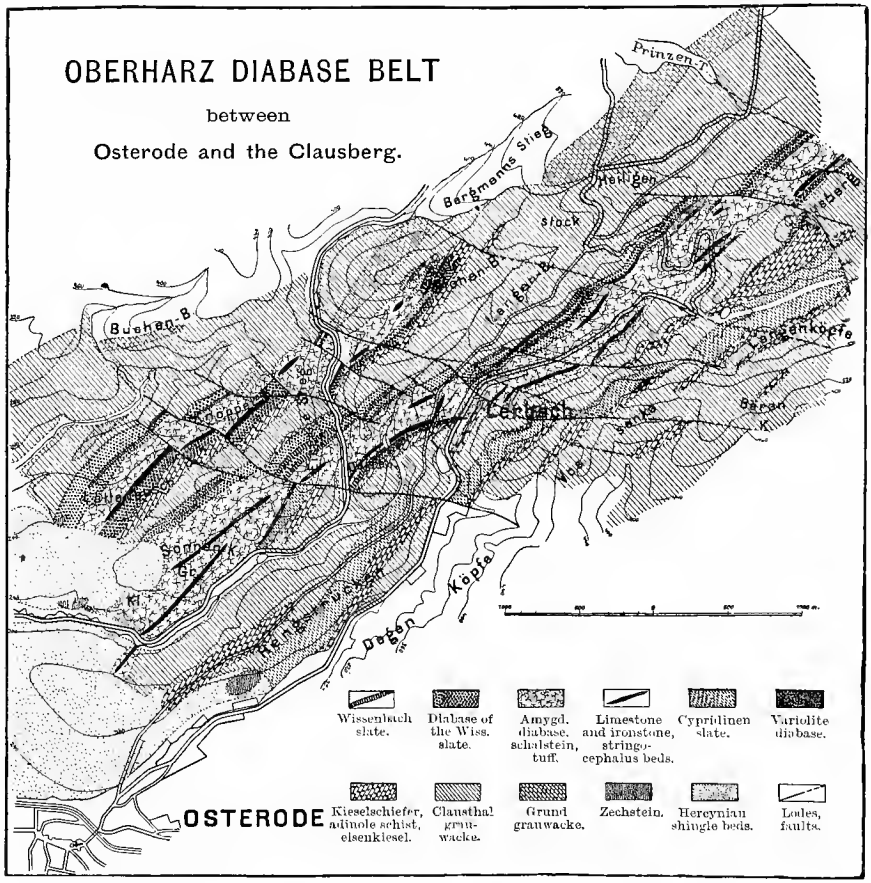


FIG. 35.—Lateral displacement of metalliferous limestone beds by transverse faults. Oberharz diabase-belt. M. Koch.

though occasionally fissures of quite different strike and in the same neighbourhood may also be of the same age. It often happens that in the same fault-system there is among the individual fissures not only agreement in strike but also in dip. In such cases if at each succeeding fault a similar downthrow is produced, 'step-faulting' results. This faulting which is illustrated in Figs. 36 and 37, is very often found along the margins of

tectonic elevations. If two faults dip towards one another, as indicated in Figs. 38 and 39, the sunken portion between them is known as a 'tectonic depression';[1] when they dip away from one another in the manner shown in Figs. 40 and 41, the raised portion between them is known as a 'tectonic elevation.'[2]

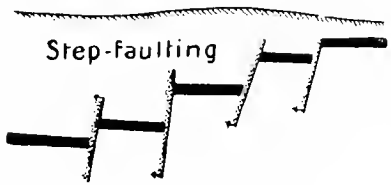


Fig. 36.—Section.

Fig. 37.—Plan.

Figs. 36, 37.—Section and plan of step-faulting.

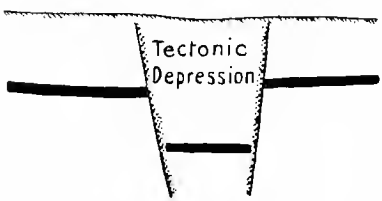


Fig. 38.—Section.

Fig. 39.—Plan.

Figs. 38, 39.—Section, with horizontal beds, and plan, with inclined beds, of a tectonic depression.

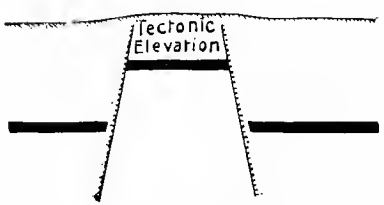


Fig. 40.—Section.

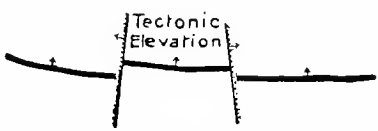


Fig. 41.—Plan.

Figs. 40, 41.—Section, with horizontal beds, and plan, with inclined beds, of a tectonic elevation.

The records of the earth's geological history show that every place has not been subject in the same measure to faulting but that a district once visited has usually been the one to suffer again from fresh disturbance at later geological periods. The consequence is that in one and the same district faults of various ages are usually found, these affecting one another in a

[1] *Graben*.

[2] *Horst*.

manner discussed later when dealing with lodes. In addition, experience shows that pre-existing fissures may also at times become re-opened whereby their total throw is increased.

The Unravelment of Faulting.—The principle followed in unravelling a fault is presented most simply where a vertical downthrow in the hanging-wall of the fault has been the only movement. The direction in which the sunken portion has moved can then be determined from the striations upon the fault-plane these being either vertical or very nearly so. Zimmermann's rule applies in such a case, this rule being: 'If the fault be approached from the side of its hanging-wall then after it has been passed the lode must be sought by going into the hanging-wall, but if the approach be from the foot-wall then beyond the fault the lode must be sought in the foot-wall.'

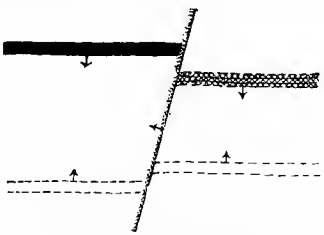


Fig. 42.—Assuming a syncline.

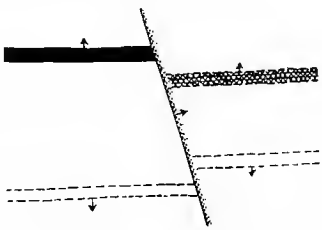


Fig. 43.—Assuming an anticline.

Figs. 42, 43.—Illustrating the search for the faulted portion of an inclined deposit at the surface by assuming that it is either one limb of a syncline or one limb of an anticline. The deposit is the full black streak, the assumed other limb is dotted, the faulted portion sought is hatched.

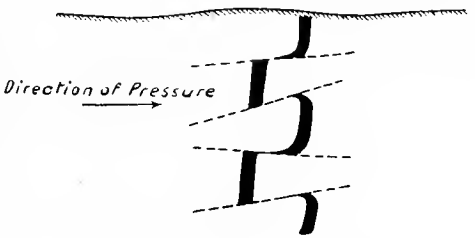
Experience has shown that this rule is far from leading to the desired result in every case because as mentioned above a more or less considerable turning of the mass takes place as it sinks. Since it is not known beforehand whether or not a simple vertical movement only has taken place, it is most necessary to determine the direction of the movement by careful observation of the striations upon the fault-planes, which striations may often be observed to descend not at an angle of 90° but at some lower angle. This it is advisable to follow. By subsequent development work, which in complicated cases is best undertaken in the fault itself, it may even be found that the direction taken by the striations repeatedly changes, indicating upon the whole a curved downthrow. Where dragging or flexure occurs along a fault the direction which this takes constitutes a further index to the position of the faulted portion of the deposit.

The unravelment of faulting from a plan often causes more difficulty to the beginner than when a transverse section is available. It is of assistance to regard the deposit as one limb of an anticline or of a syncline, and to bear in mind that while the latter in sinking becomes wider, an anticline

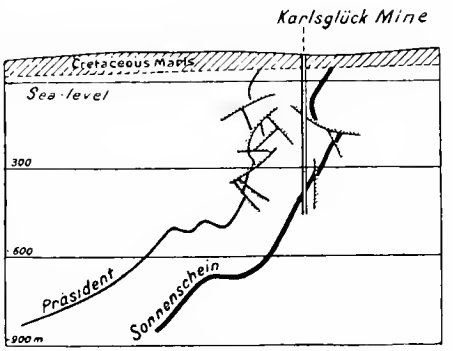
becomes narrower. The two diagrams given in Figs. 42 and 43 are thus obtained. In cases where several movements have taken place along one and the same fault it is usual to find the striations of the last movement only, the direction of which need not necessarily represent the composite direction of the faulting.

4. *Vertical Displacements.*

These break the continuity of a deposit along the dip and arise when, by the action of horizontal pressure, a portion of the beds bounded above and below by flat-lying fractures becomes severed and pushed forward together with whatever section of the useful deposit is enclosed within it. This position is illustrated in Fig. 44. That the several portions of a deposit so displaced when the disturbance is complex belong to one and the same original deposit, may be gathered from the way the beds are dragged in the direction of displacement. In this direction the deposit becomes bent and then pinches out, often at a clay parting in which, until the other terminal of the deposit is reached, fragments of ore are found more or less frequently. This other terminal begins, as the first ended, with but little width though this quickly increases till, after bending again, the deposit resumes its normal width and standing. In addition to fragments of ore between the two terminals, striations upon the plane of movement serve also as pointers; these are either horizontal or are inclined at a low angle. According to the dip of that plane the displaced portion of the deposit is more or less uplifted or downthrown.



a, Diagram.



b, Actual case in the Karlsglück mine, west of Dortmund.

FIG. 44.—*a* and *b*, Displacement along the dip by horizontal pressure. Actual case by Krusch, *Erläuterung zu Blatt Dortmund*.

These vertical displacements differ however from faults proper, which owe their effect to their dip, in that with them gravity practically plays no part. Displacement is therefore not effected by the sinking of the beds

in the hanging-wall of the fault but by movement in direct response to side pressure and independent of the dip of the plane of movement. Though this be so it may nevertheless often be observed that where the planes of movement have varying dips, particularly those sections are displaced which are so bounded as to form wedges pointing in the direction from which the pressure came. This preference is expressed in Fig. 44*a*. Concerning age, a further difference between the two classes of disturbance exists in the fact that while with normal faulting the fault is older than any movement along it, with vertical displacement fracture and movement were often contemporaneous. Where in consequence of the dip of the plane of movement the beds in its hanging-wall have settled down, there is in plan no difference to be distinguished between such vertical displacements and normal faults; in all other cases the respective representations in plan are quite different. There is therefore no connection between either the

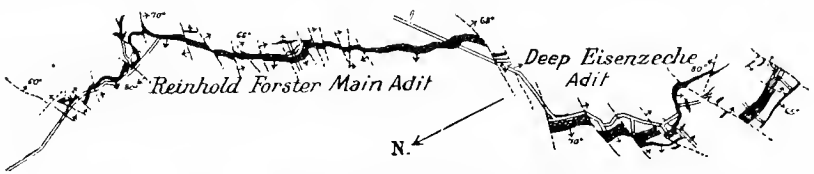


FIG. 45.—Horizontal displacements of the Eisenzeche lode-series in Siegerland, taken from the official description of the district.

dip of the fracture or that of the deposit on the one side, and the direction of displacement on the other.

Vertical displacements differ also from overthrusts, firstly, because it is far from true to say of them that older beds are always pushed over younger, and secondly, because of the simple nature of the drag or bending in the direction of movement, which bending cannot be mistaken for the complicated disturbance which occurs with overthrusts.

UNRAVELMENT.—The unravelling of vertical displacements is comparatively easy. The drag of the deposit at the plane of movement indicates the direction in which the displaced portion has travelled. Either then that plane is followed in the direction indicated till ore-fragments lead to the re-discovery of the deposit, or it is penetrated and work is undertaken in the ground beyond.

5. *Horizontal Lateral Displacements.*

These disturbances to which, in addition to the others mentioned, deposits may be subjected, result from the action of a horizontal pressure upon a complex which though already traversed by fractures has not yet

suffered any material disturbance, the effect being that, as illustrated in Fig. 45, different sections of the complex are moved horizontally and independently of one another transversely to the strike. Such lateral displacements are characterized by horizontal striations upon a vertical plane. No sinking worth mentioning takes place. The picture presented in plan is at first glance quite similar to that of such normal faulting as wherein the appearance of lateral displacement results from sinking in the hanging-wall. The difference in principle however between the two classes lies in the fact that while with normal faulting the direction of the displacement is a function of the dip of the deposit and of that of the fault, with

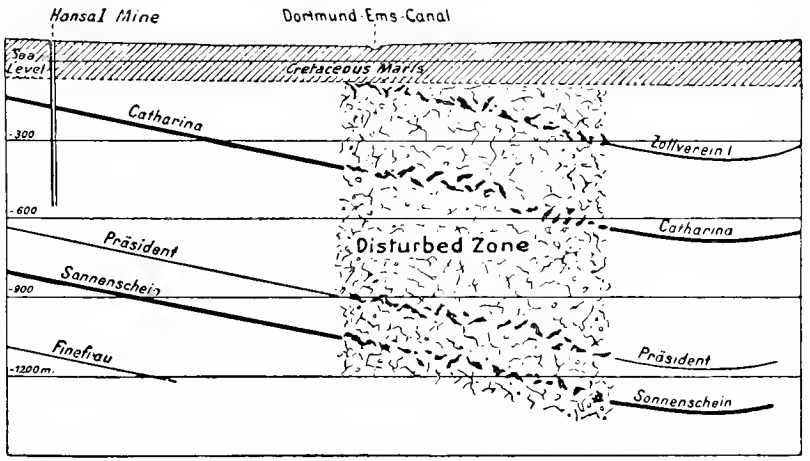


FIG. 46.—Powerful disturbance zones without influence upon the general position of a deposit. Hansa mine, north of Dortmund. Krusch, *Flözprojektion zu Blatt Dortmund*.

lateral displacement no such connection exists. These have little concern either with the dip of the deposit or with that of the fracture, but are entirely dependent upon the direction of the pressure. Since fracture in a country never takes place along a narrow and smooth plane, angular pieces of ore torn off from the inequalities of the original plane of movement may often be found between the two portions of a formerly united deposit. Such fragments as these are of service as pointers to the direction of the displaced portion.

UNRAVELMENT.—The unravelling of lateral displacements has lately been of practical importance in Siegerland. The country-rock being in all cases affected in the same way as the deposits, any particular bed easy to recognize on account of its petrographical or palæontological characteristics will naturally be displaced in the same direction as the deposit. A careful geological survey of the surface such as would dis-

close the extension of this characteristic bed would consequently in most cases lead at the same time to the discovery of the lost portion of the deposit.

In addition to the different classes of disturbance mentioned, the

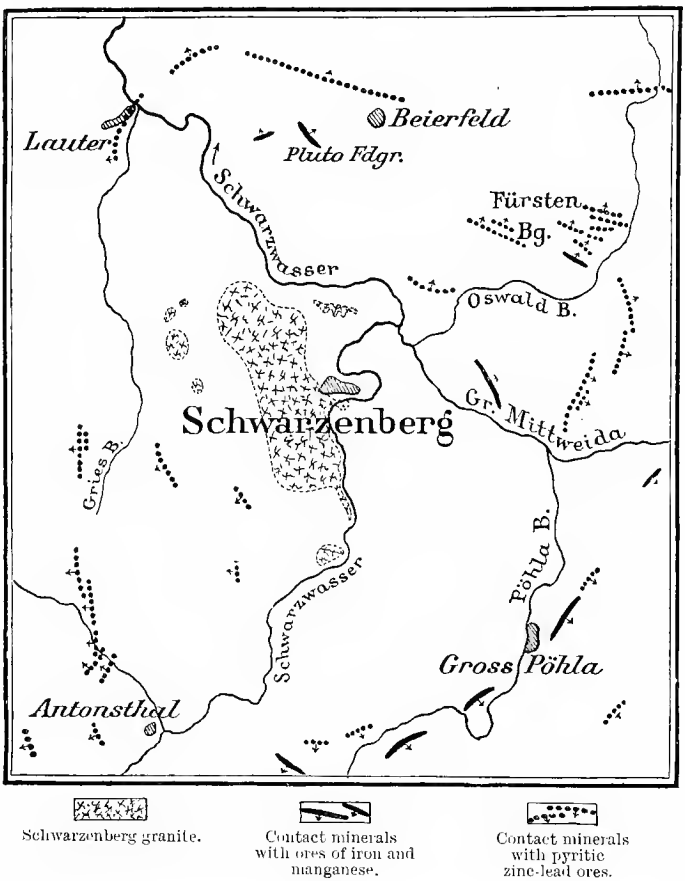


FIG. 47.—Ore-deposits in the granite contact-zone at Schwarzenberg in Saxony. *Blatt Schwarzenberg der Geol. Spezialc Karte.*

comparatively rare case must also be considered in which, though a disturbed zone of great width may be present, no displacement of the deposit either before or behind the disturbance, is produced. Fig. 46 illustrates a well-known example of an occurrence of this sort at the Hansa I. mine, near Dortmund.

II. Form of the Epigenetic Deposits

(*a*) *Contact-Deposits.*

'Contact-deposits' are those occurrences which have originated within the material of the earth's crust through the action of volcanic magma at a high temperature, especially when this magma was under pressure and its contained gases and fluids had no escape to the atmosphere. These deposits are therefore essentially the products of intrusion. The zone thus subjected to metamorphism and of which the outer border keeps more or less parallel to that of the intrusion, is termed the 'contact-zone.' In it the ore-deposits are usually concentrated in the immediate neighbourhood of the intrusive or not far from it. Close to the actual contact of this rock with that through which it was forced, fragments of the latter are often found embedded with the ore in the intrusive. As will be stated in the section dealing with the origin of contact-metamorphic deposits, these occurrences are usually the result of the alteration of limestone, sometimes to oxide and sometimes to sulphide ores.

The above genesis postulates that contact-deposits in their form and arrangement follow the borders of the solidifying intrusive; the occurrences are in fact and as illustrated in Fig. 47, often found arranged around that mass in several almost parallel rows. Since however they are at the same time dependent upon the chemical properties of the country-rock and to such alteration limestone and dolomite are particularly favourable, the general distribution of these deposits must in general follow that of those rocks. This position is illustrated in Fig. 48.

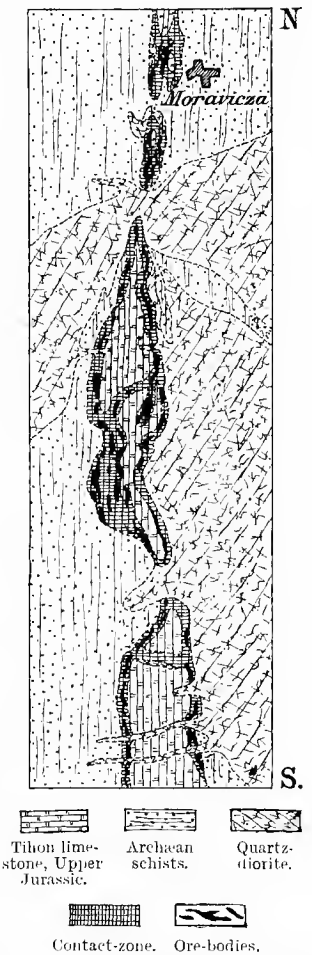


Fig. 48.—Disposition of the contact-deposits in the Banat, showing their association with limestone.

In themselves contact ore-bodies exhibit a lenticular or irregular columnar form. The expression *stock* so much used in German, and

of which the expression 'chimney' appears to be the best equivalent in English, refers to ore-bodies generally of irregular outline, which have but little length though their width is relatively great and their extension in depth is considerable. Such ore-bodies are illustrated in Fig. 49. Where the outline is more regular it will generally be found to have taken unto itself that of the intrusive or that of the country-rock. Since with intrusion much fracturing of necessity occurs, many true lodes are found in

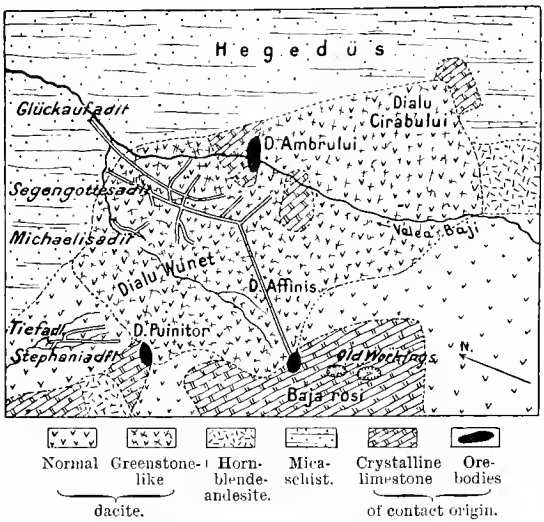


FIG. 49.—The Siebenbürgen pyritic contact-deposits. Semper, *Die Golderzlagerstätten Siebenbürgens.*

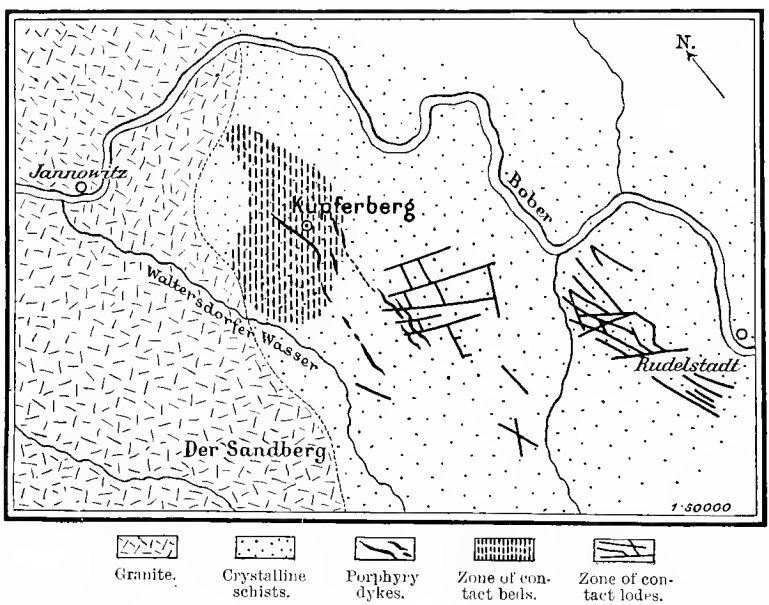


FIG. 50.—Contact ore-deposits of Kupferberg in Silesia, the contact beds being found nearer to the granite, the contact lodes farther away.

close connection with contact-deposits, in the which case it is only from the character of the minerals they contain that it is possible to determine that they are associated with this class of deposit. The occurrence of such lodes at Kupferberg in Silesia is illustrated in Fig. 50. Their further description in this work is given under the heading of contact-deposits. Again, since the contact processes resemble the metasomatic in so far that it is particularly limestone and dolomite which become altered, contact-deposits show great similarity in form to those resulting from metasomatism. Between the two classes, in these cases also, the mineral content becomes the deciding factor.

FIG. 51.—Simple gold lode with many fragments of trachyte country-rock, Nagyag.

Among contact-deposits there are some of very considerable dimensions, as for instance the iron deposits of Elba, the Banat, and the Urals ; in general however they are small. The work of prospecting and following them is in all cases rendered considerably lighter by the plainly recognizable contact-zone, though on the other hand the actual winning of the ore and the estimation of the ore-reserves are rendered difficult by reason of the general irregularity in outline.

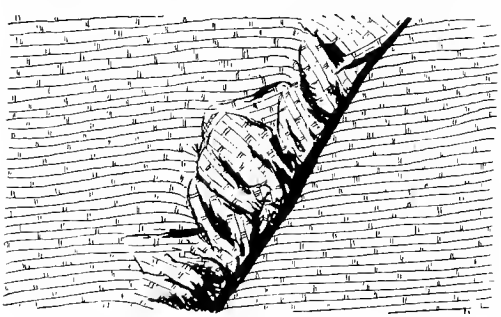


FIG. 52.—Composite lode in the sense of Cotta or Naumann.

(*b*) *Cavity-Fillings : Lodes and Chamber-Deposits.*

The most important representatives of this group are the lodes. These are fissures filled with ore, this filling being often accompanied to a greater or less extent by impregnation. Each 'simple lode,' as illustrated in Fig. 51, is the tabular filling of a fissure, that is of a cavity standing more or less open. In the hanging-

wall and in the foot-wall the lode material is generally sharply separated from the country-rock. When such a wall is further marked by clayey

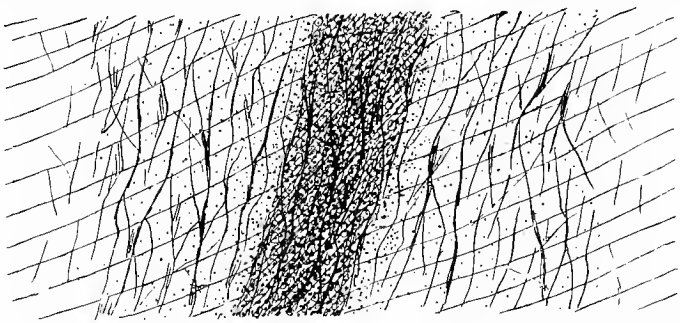


FIG. 53.—Composite lode in the sense of Krusch. Telluride lode in the Kalgoorlie district, Western Australia.

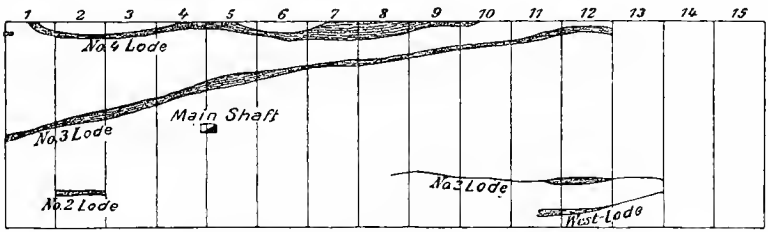


FIG. 54.—Horizontal section at the 200 ft. level.

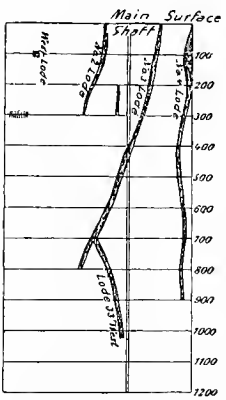


FIG. 55.—Vertical section 400 feet from the north boundary.

FIGS. 54, 55.—Composite lodes of the Golden Horseshoe mine, Western Australia, having in consequence of complete silicification of the intervening rock the appearance of simple lodes. Krusch, *Zeit. f. prakt. Geol.*, 1903, p. 328.

material this material is known as 'gauge' or 'selvage.' The width of simple lodes, that is the vertical distance between the walls, is as a rule not more than one or two metres.

'Composite lodes' in contradistinction to simple lodes, are chiefly formed when after the formation of a fissure the hanging-wall breaks and its material falls into the still unfilled space. The fissure becomes then a wide disturbed zone which in the foot-wall is often separated from the country-rock by gauge resulting from the grinding of the rock surfaces, while in the hanging-wall it passes gradually over to undisturbed rock. Then in this zone the spaces between the rock fragments become filled with ore and gangue deposited from mineral solutions, in such a manner

that in a section across the width pieces of ore, more or less large, alternate with rock fragments. Such lodes are termed 'composite lodes' in the

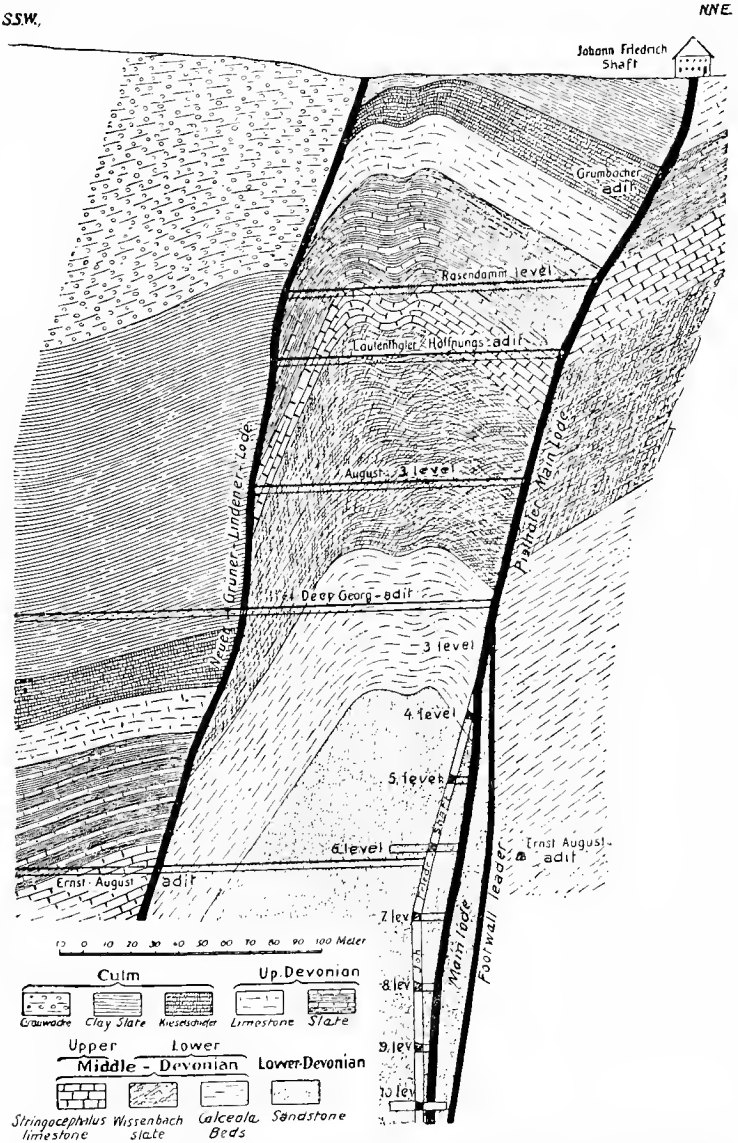


FIG. 56.—The Neuer-Grüner-Lindener and the Pisthal lodes in the Oberharz district, occurring as faults. E. Maier, *Zeit. f. prakt. Geol.*, 1901, p. 196.

sense of Cotta and Naumann who proposed this term for them. They are illustrated in Fig. 52.

Not less important is a second type of composite lode suggested by Krusch,[1] which consists of a number of small veins between which the country-rock is impregnated with ore or metasomatically replaced by gangue. Such a lode is illustrated in Fig. 53. It is often doubtful whether such zones owe their formation to tension or to pressure. In all cases however they are essentially mineral zones in which cavity-filling on account of the small cavity-width has played but a subordinate part though the country-rock between is sometimes so completely silicified that to all appearances one single and large lode is formed. With this type of composite lode no sharp wall exists either in the foot-wall or in the hanging-wall, but on both sides the lode material passes gradually over to unaltered country-rock. The economic width is therefore determined by the perfection to which mining and treatment have attained, since all mineralized material from which a profit may be made is mined. The

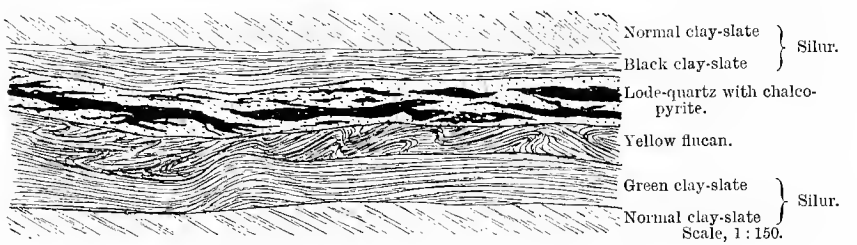


Fig. 57.—Bedded copper lode at Kitzbühl in the Tyrol.

width of such lodes therefore in the cases of long-lived mines generally increases with advance in treatment and improvement in communication. Among others, a large number of the telluride lodes of Western Australia, illustrated in Figs. 53, 54, and 55, belong to this type. Contrary to narrow simple lodes, composite lodes have usually considerable width, this reaching sometimes to 50 m. or even to 100 m. The fact that with such lodes no sharp boundary against the country-rock exists, is naturally a possible source of error when making a valuation.

Simple as well as composite lodes have a tabular form. In this therefore they exhibit great similarity to ore-beds, from which they differ however in that their extension in all directions is generally smaller and in that they generally cut across the formation, often as in Fig. 56, faulting it, while ore-beds are always conformably interbedded. Should perchance a lode coincide in strike and dip with the country-rock, as does that illustrated in Fig. 57, there is then, as far as form is concerned, no difference remaining between it and an ore-bed. Even then however, and irrespective of a possible difference in mineral content, there would remain

[1] *Zeit. f. prakt. Geol.*, 1903, p. 323.

the difference that the lode is younger than the country-rock, while under ordinary conditions the ore-bed is younger than its foot-wall and older than its hanging-wall. Since fissures have a limit both in strike and dip the tabular form of a lode eventually gives way in both these directions to a lenticular form as the lode pinches out. It is customary to regard as lodes only such deposits as fill those fissures where the space to be filled was more or less tabular.

When a fissure crosses beds of different petrographical character, its form, and consequently that of the deposit within it, is generally found to undergo some modification. In compact sandstone for instance a fracture is usually clean; in soft slate however it more often splits to form a broken zone in which country-rock decidedly preponderates. In readily soluble rocks such as limestone or dolomite, a fissure occasionally enlarges itself by subsequent solution of the country-rock, to form irregularly shaped cavities or chambers. Such cavities, in consequence of the numerous fractures and bedding-planes which serve as points of attack for the solutions, often form a complex system; should they then become filled with ore such deposits are no longer termed lodes but are described as 'chamber deposits.' These appear more or less pipe-like, their length coinciding with the extension of the principal fissure or with that of the bedding-planes. Deposits of this class are not infrequently of large dimension, though irregularity in form often renders mining and the estimation of quantities very difficult.

(*c*) *Metasomatic Deposits.*

These deposits are formed only where the country-rock is easily dissolved and therefore principally in limestone and dolomite, masses of which rocks, while maintaining their form, becoming very gradually replaced by ore. These deposits are almost invariably connected with fissures and faults, generally containing some ore, which have served as channels of access for the mineral solutions. Such a connection is illustrated in Fig. 58. While with lodes and chamber-deposits the form is only dependent upon the original shape of the cavity, with metasomatic deposits the shape of the mass undergoing alteration also plays a part. In cases of complete alteration, such as is illustrated in Fig. 59, it is the shape of this mass which determines that of the deposit. In this respect two classes of metasomatic deposits may be differentiated, namely, those of manganiferous iron and those of lead-zinc.

At many places on the earth's crust beds of limestone of widely differing age—at Bilbao, Cretaceous; at Kamsdorf, Zechstein; in Cumberland, Carboniferous—have been altered to more or less manganiferous iron ore, the process of this change being that siderite first became formed, from

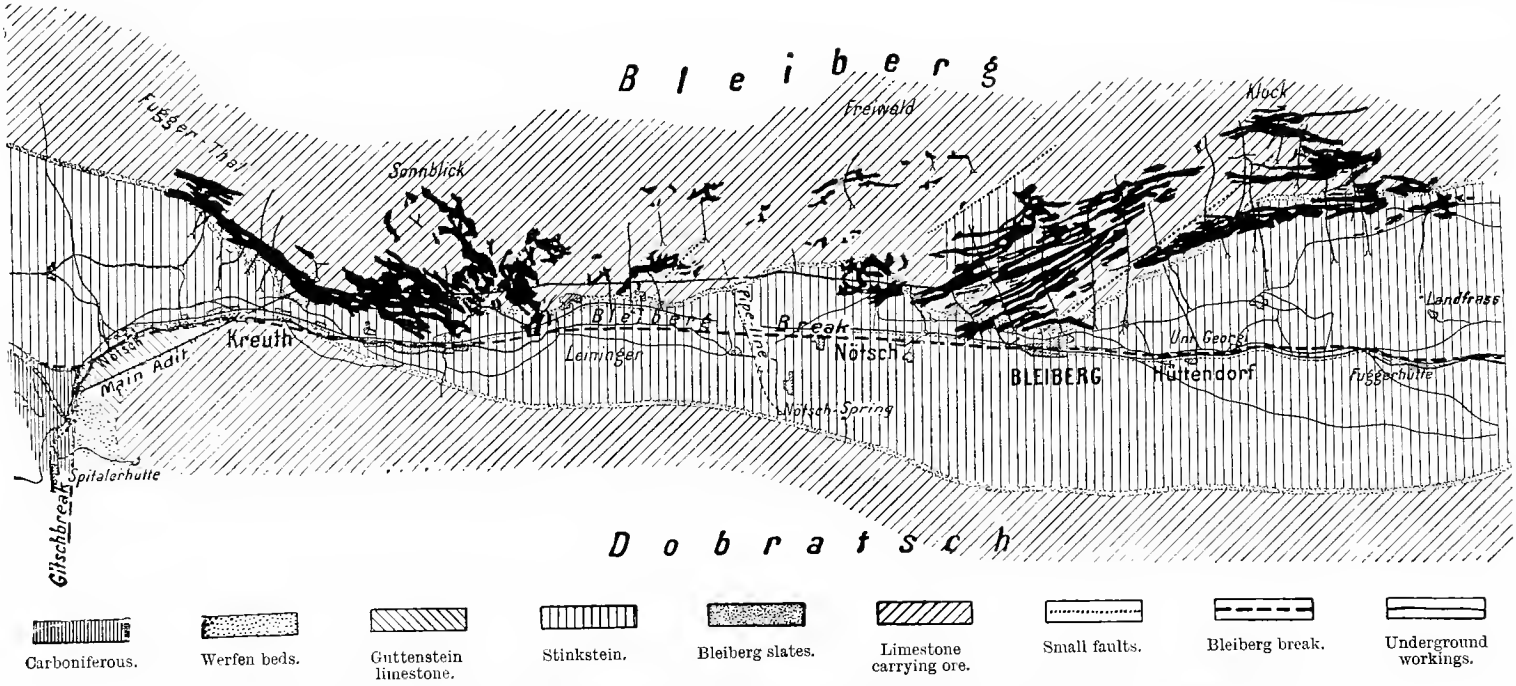


FIG. 58.—General geological map of the Bleiberg district in Kärnten, showing the Bleiberg Break and the deposits associated with it. Hupfeld, *Zeit. f. prakt. Geol.*, 1897, p. 237.

which in turn limonite and hæmatite resulted. With deposits of this type the actual filling of the fissure through which the mineral solutions arrived, generally plays no material part. It often happens, as illustrated in Fig. 59, that an entire limestone bed is completely replaced. The form of the metasomatic manganiferous iron deposit then completely resembles that of an ore-bed. It is however usually the case that complete alteration only takes place in the neighbourhood of the channels of access, receding from which the amount of alteration gradually but surely

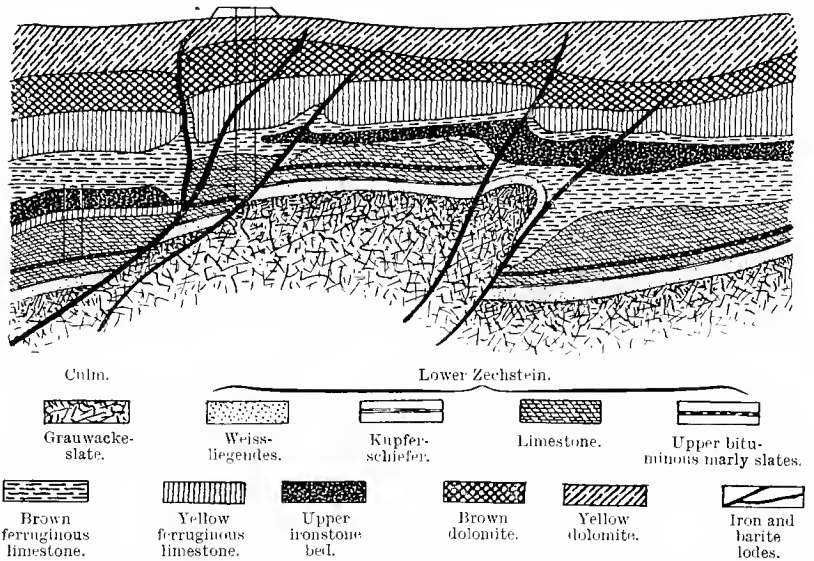


FIG. 59. — Metasomatic iron deposits at Kamsdorf in Thüringen, showing the dependence of the form of an ore-bed upon that of a limestone mass. Beyschlag, *Jahrb. d. prakt. geol., Landesanst.*, 1888, p. 329.

diminishes till the iron ore becomes limestone rich in iron, which in its turn gives place to unaltered rock.

With the lead-zinc ores of this class the case is essentially different. The solutions pregnant with these ores appear to have set about the alteration of the limestone less energetically, so that only in quite exceptional cases has this rock completely disappeared. Generally the occurrence is one of irregular ore-bodies formed, as illustrated in Fig. 60, along the bedding- and fracture-planes of the limestone, and exhibiting a pipe-like shape which gives to them a certain resemblance to the cavity-fillings described on p. 41, with which deposits they are almost invariably associated. Should the alteration be more complete an irregular ore-body arises which, in so far as its form is concerned, may possess great similarity to contact-metamorphic deposits. All gradations in form between the pipe-like and

the chimney form are found. Moreover, generally though not always, there is no sharp separation from the country-rock, in consequence of which and of their irregularity the development of these metasomatic deposits is a work of considerable difficulty.

Under especially favourable conditions metasomatic alteration may proceed from one face only, as for instance when limestone lies on impervious slate. Knowledge of the fact that metasomatic deposits almost without exception occur in close relation to fissures, lodes, faults, or chamber-deposits, is of great service in establishing the general connection between the different and usually numerous bodies forming part of any comprehensive occurrence. These bodies are only found within a zone extending along a fissure or break, and their occurrence is further limited to such rocks as surrender to metasomatic alteration. It is particularly at the contact of impervious beds with limestone that these deposits are found congregated, because there the impervious beds dam back the mineral solutions. In fixing the length of a mining property, this fact has to be taken into consideration.

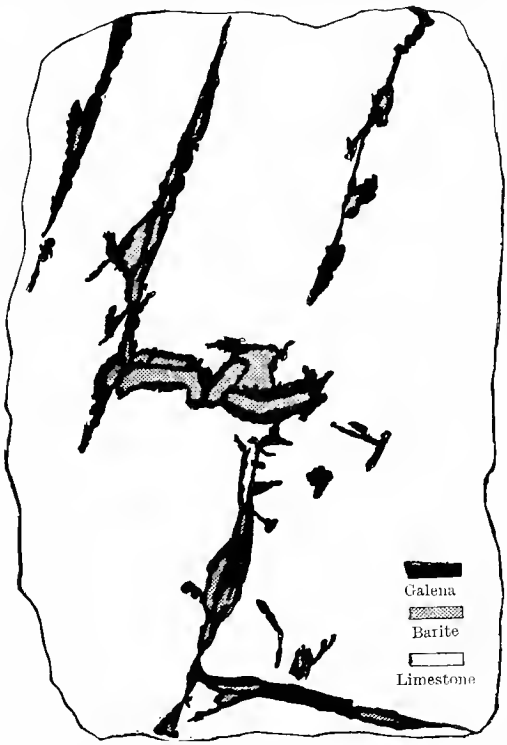


FIG. 60.—Metasomatic ore following pipe-like the bedding-planes and fissures in limestone at Bleiberg. Hupfeld, *Zeit. f. prakt. Geol.*, 1897, p. 245.

(*d*) *Impregnations.*

When solutions containing heavy metals find their way along fissures or bedding-planes into a bed which, while porous, is not or is only to a small extent soluble, then the pores of that bed may become filled with ore. In such a case an ore-deposit eventually arises which in greater part still consists of rock material and which therefore, speaking generally, retains

the form of the original bed. In an impregnated zone thus formed the ore is younger than the rock. As a rule it diminishes in amount on both sides with distance from the planes of access, so that, as illustrated in Fig. 61, a gradual passage from the impregnated zone to the original rock occurs. When the bed becomes completely altered the form of the resulting deposit is naturally that of a bed; on the other hand with incomplete change it remains irregular. In any case the ore-body usually shows its greatest thickness along the channels of access, on both sides of which it passes gradually, though along no regular line, into normal rock.

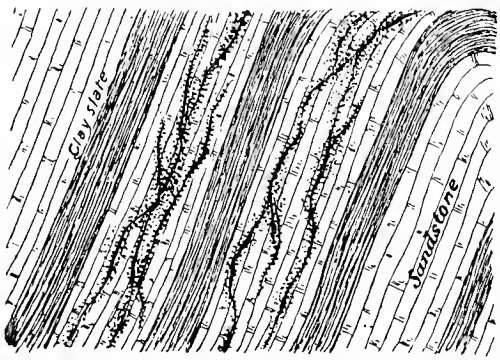


FIG. 61.—Impregnations of copper ore, malachite, in the Miocene sandstone of the copper district of Los Arcos and Mues in Northern Spain.

To this class of ore-deposit, the concretionary deposits and fahlbands may also be considered to belong. Concretionary deposits may be primary, that is formed during the original consolidation of the rock, or secondary, that is formed after that consolidation. If for instance heavy metals be in solution in a mudstone not yet consolidated, it often happens that these do not remain evenly distributed throughout the still soft material, but collect at points which on account of special chemical or geological circumstances are peculiarly suited for ores to crystallize out of solution. Thus, concretions of clay ironstone are generally found around organic remains, as with the clay ironstone kidneys of the *Rotliegendes* at Lebach and the clay ironstone concretions in the Coal-measures, this latter occurrence being illustrated in Fig. 62. Concretionary deposits may also be formed in clayey sand and in sandy clay, even long after their deposition, should these become saturated with solutions from out of which ores may crystallize. The only necessary condition would be that the beds were not completely impervious. The form of such secondary concretionary deposits, which originate also by concentration around specially suitable nuclei, is exactly the same as the primary; as a rule however they are not so often met. They are illustrated in Fig. 63.

FIG. 62.—Clay ironstone concretions in the hanging-wall of the main seam in the lean portion of the Westphalian coalfield; these concretions, containing *Goniatites*, represent a marine horizon.

The greatest factor affecting the form of these deposits is that of the bed to which their occurrence is limited. If the deposit be primary, then the concretions are found either separate from one another in a definite horizon of the bed, or so close together that an almost compact body results, in which case the form of the deposit, as illustrated in Fig. 64, practically does not differ from that of an ordinary ore-bed; such occurrences might even just as well be considered under that class. Secondary concretions on the other hand are generally irregularly distributed in their bed.

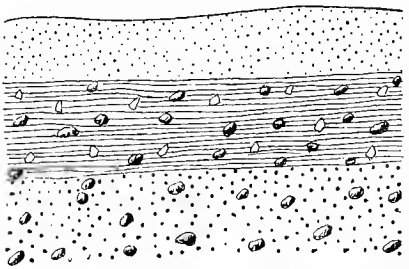


Fig. 63.—Limonite concretions representing decomposed siderite of secondary formation in glauconite marl and Miocene glauconite sand. Mould-sand quarry west of Lingen on the river Ems.

The fahlbands which may also be considered here, are not all of one origin. Petrographically they are crystalline rocks in which particles, crystals, or nests of chalcopyrite, pyrite, or pyrrhotite, occur to such an extent that the rock, especially in its weathered condition, is distinguished from those surrounding it by its brown colour. Formerly the term 'fahlband'—the name arises from the faded colour of the weathered deposit—was limited to those occurrences in which the pyrite was, as suggested in Fig. 65, ostensibly contemporaneous with the rock, this rock belonging to the crystalline schists. But with such a definition difficulties arose because magmatic deposits in eruptive rocks, in regard to their petrography, agree exactly with typical fahlbands, or at least in so far as the distribution of their pyritic particles is concerned. Later investigation has shown that the genesis of even those fahlbands which were regarded as typical is open to dispute, since the rocks which from their appearance have so far been regarded as belonging to the crystalline schists are more often in fact regional-metamorphic rocks whose pyritic content first arose during metamorphism. It is therefore advisable when defining the meaning of the term 'fahlband' to renounce the

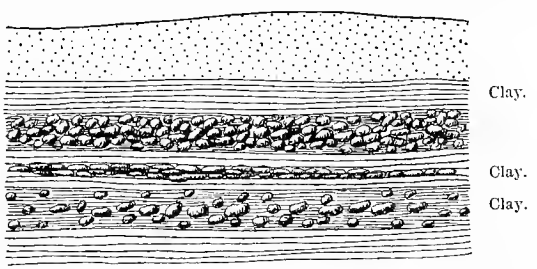


Fig. 64.—Beds of ironstone concretions in the dark-coloured gault clay at Ahaus in Westphalia.

claim that the pyrite is primary, and to keep in preference to purely petrographical distinctions.

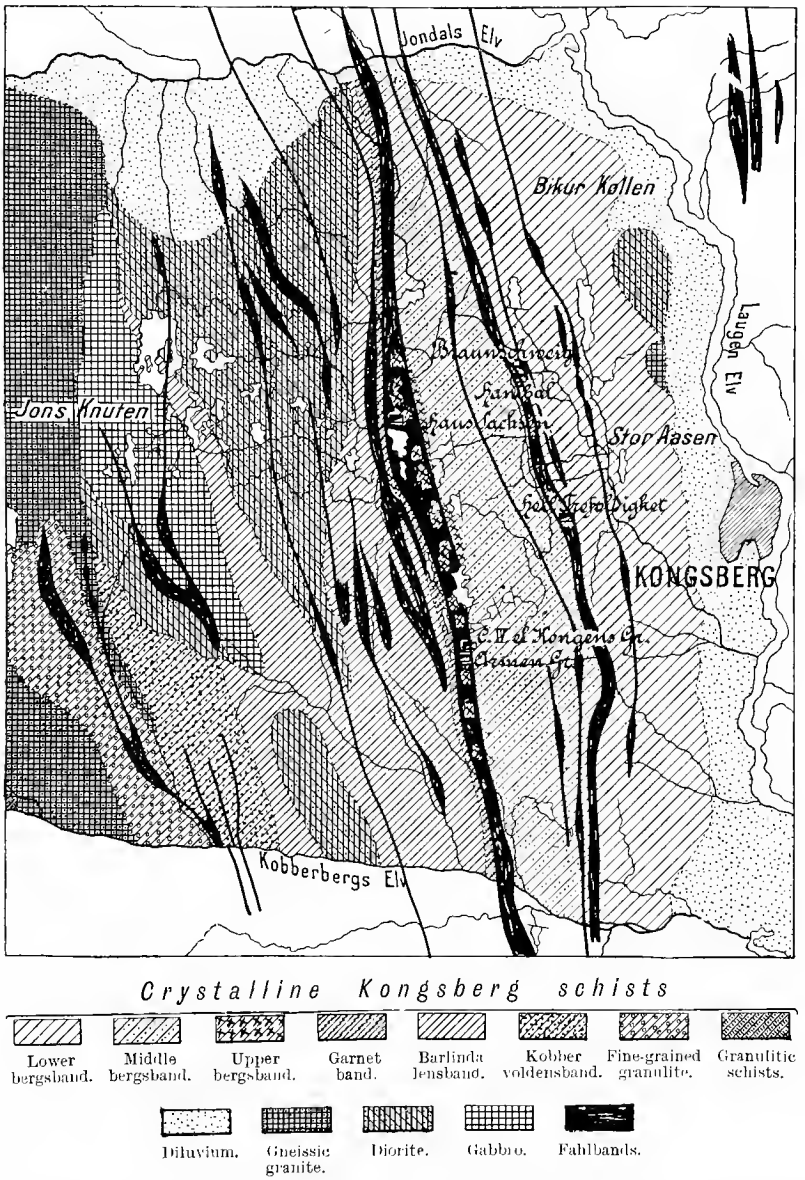


FIG. 65.—Fahlbands at Kongsberg. Scale, 1 : 79,400.

The form of fahlbands—which deposits it may here be mentioned are

of but small economic importance—is that of the enclosing bed, or in other words that of an ore-bed. Passing as they do both in strike and dip gradually over to rock free from pyrite, the extension of the fahlband

Fig. 66.—Diagram of a fahlband showing the relation between the metalliferous lens and the whole bed.

is less than that of the bed. The relation between the two is best described as that of two lenses, one within the other, of which the one inside is the fahlband. This position is illustrated in Fig. 66.

Disturbances of the Epigenetic Deposits

First among these come those disturbances which have already been described under the syngenetic deposits. In particular those which affect impregnated and metasomatic deposits, or at least the metasomatic manganiferous iron deposits, agree almost completely with the disturbances of the syngenetic deposits; folds, overthrusts, faults, vertical displacements, lateral displacements, all are found to occur, but folds and faults most frequently. Contact deposits and cavity-fillings, in consequence of their form and origin, are less liable to disturbance by folds and overthrusts, and of the three remaining classes of disturbance, faults are with these two classes of deposit the most numerous. All that has been said under syngenetic deposits concerning the formation, the properties, and the unravelment of the different disturbances, holds good here also. To those disturbances however another must here be added, namely 'deflection,' to which however lodes only are subject.

Lode Deflections.

These disturb a lode along its strike. The lode stops at a fissure or at some other obstacle such as a difference of rock, after crossing which, as illustrated in Figs. 67 and 68, it resumes its course again though a little out of line. The appearance of a deflection in plan is therefore similar to that of a true fault, though there exists no regularity in the manner or direction of this class of dislocation. This essential

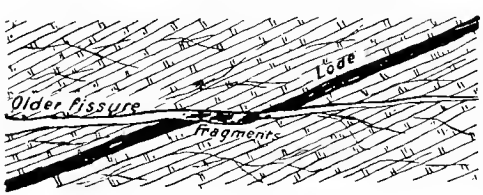


Fig. 67.—Lode deflection.

difference between the two classes of disturbance is based upon their different genesis. Deflection results when at the formation of a lode fracture, older fissures or obstacles were already present producing a deflection of the younger fracture which, upon arriving at the older disturbance, followed this for a longer or shorter distance till at some favourable point it branched off again into the country-rock, continuing its course there with approximately the same strike as before. Since the obstacle causing such a deflection is older than the lode this latter does not actually stop at the obstacle, but generally continues within it though often much split up. Deflections are therefore similar to 'kinks'[1] wherein without apparent cause a displacement in strike is presented, doubtless brought about by some change in the effect of the pressure in operation. Such a kink is illustrated in Fig. 69. Since deflections are due to differences in the cohesion of the rocks enclosing the fissure, the direction in which a lode becomes deflected is not dependent upon its dip or upon that of the obstacle. In this fact lies a second essential difference between deflections and faults.

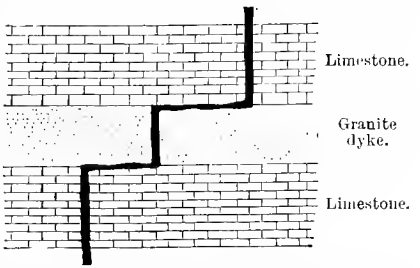


FIG. 68.—Double lode deflection from the St. Olaf lode. Vogt, *Zeit. f. prakt. Geol.*, 1902, p. 4.

FIG. 69.—Kink in a newly opened pyrite vein in a lode. Traugott lode. Freiberg district. Two-thirds natural size.

Since no complete cutting off of the lode actually occurs, the unravelment of deflections is most simple. The shattered lode is followed in the deflecting obstacle till the place is discovered where it again enters the country-rock and resumes

[1] *Hakenschläge.*

its previous strike. Again since, as will be stated later in the chapter upon mineral formation, the deposition of ore is in part dependent upon the physical properties of the country-rock and in cases of deflection the material of the pre-existing obstacle differs essentially from the country-rock, it is usual to find that portion of the lode within this material different from the lode in the principal part of its course.

Graphic Representation of Deposits

A clear presentation of the form of a deposit can only be furnished by the most complete graphic representation, and the miner therefore from the beginning has called to his service the art of surveying. The different survey plans which come in question are :—

1. The ground plan, that is the projection of all the workings upon a horizontal plane.
2. The longitudinal plan, that is the projection of all the workings upon a vertical plane parallel to the strike.
3. The stoping plan, that is the presentation of those workings situated upon the plane of the general strike and dip.
4. Sections :—
   (*a*) Transverse sections, made at right angles to the strike and at different points.
   (*b*) Longitudinal sections, made parallel to the lode and at different points.

Of these drawings, the ground plan which may be looked upon as the sum of the horizontal sections at the different levels, the transverse sections, and the stoping plan, are especially important and indispensable. With regard to the first, on account of the multiplicity of the workings, it is generally better to keep separate drawings for each level. Drawings in which lengths or heights become too much foreshortened are not to be recommended and had better be avoided. Mine plans upon which all the levels are put together usually give only a general view of the extent of the workings, and when the number of levels is large, such plans are no longer able to present a clear picture of the geological circumstances of the deposit. The ore-bodies, the variations in country-rock, the disturbances, and the water-courses, should always be clearly indicated on mine plans, nor should the geological survey of the surface be omitted.

In many districts it has become the rule, by means of a number of vertical and horizontal sections at regular distances apart, to reconstruct the form of the deposit on a reduced and convenient scale. W. Petersson in 1896, for instance, represented the deposit of the Nordmarks mine,

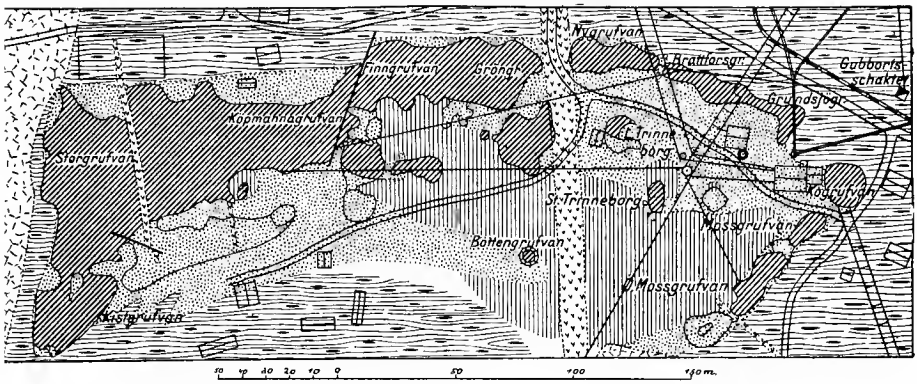


FIG. 70.—Geological map of the surface at the Nordmarks mine, Wermland, Norberg.

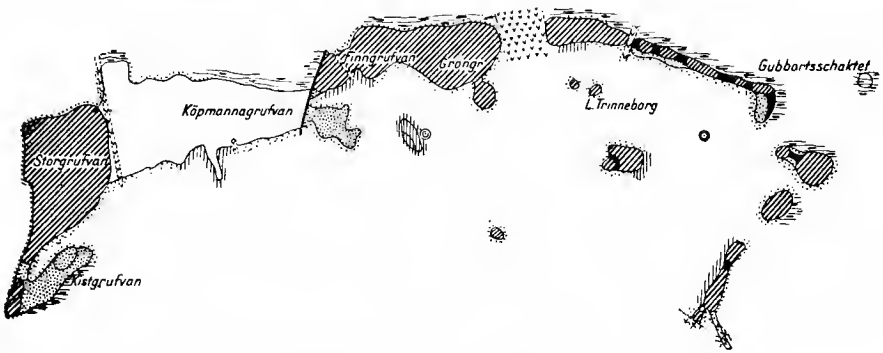


FIG. 71.—Geological map of the 1st level of the Nordmarks mine.

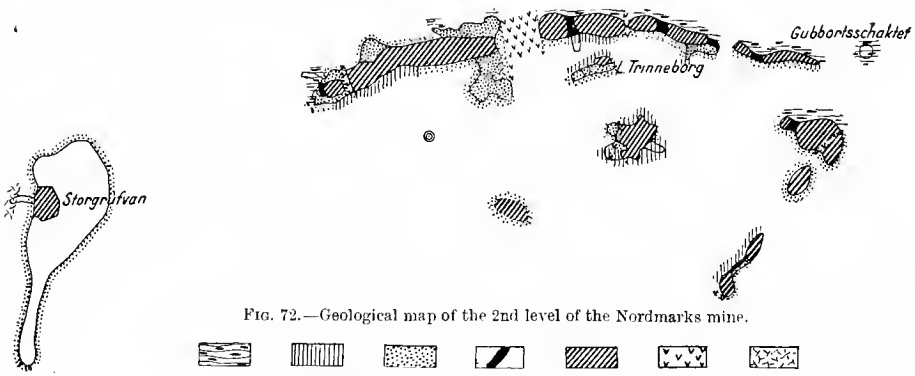


FIG. 72.—Geological map of the 2nd level of the Nordmarks mine.

FIGS. 70–72.—Geological map of the surface, and two horizontal sections of the Nordmarks iron mine, showing the behaviour of the ore-bodies in depth. Petersson.

Norberg, by means of a number of such horizontal sections which he attached as an atlas to his description and which when arranged one over

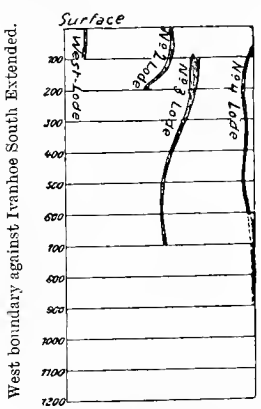


FIG. 73.—Section 200 feet from the north boundary.

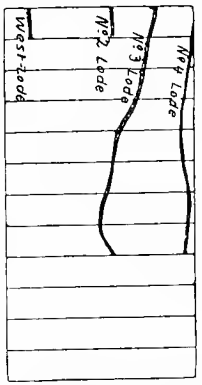


FIG. 74.—Section 300 feet fron. the north boundary.

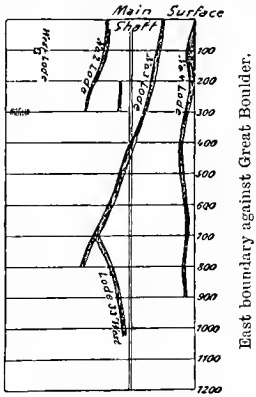


FIG. 75.—Section 400 feet from the north boundary.

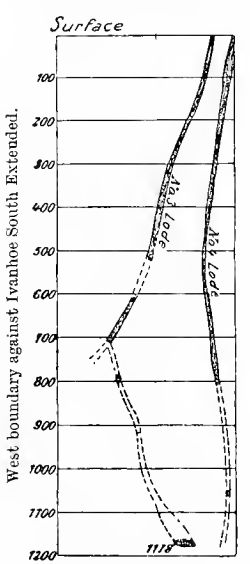


FIG. 76.—Section 550 feet from the north boundary.

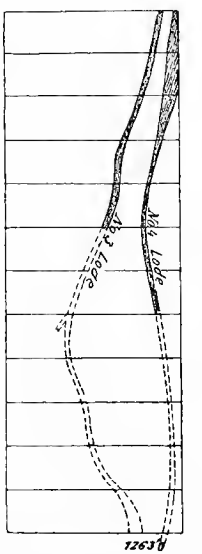


FIG. 77.—Section 630 feet from the north boundary.

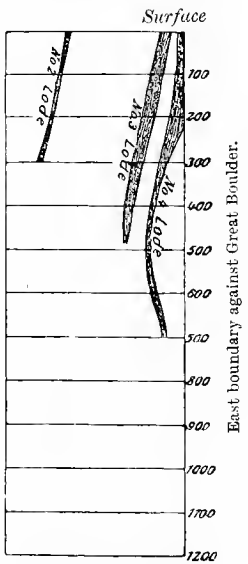


FIG. 78.—Section 700 feet from the north boundary.

FIGS. 73–78.—Cross sections of the Golden Horseshoe mine, Western Australia. Krusch, *Zeit. f. prakt. Geol.*, 1903, p. 328.

another give an excellent idea of the deposit both in vertical and horizontal relation. These sections are illustrated in Figs. 70–72. In Western Australia also, mining engineers are accustomed to give vertical sections

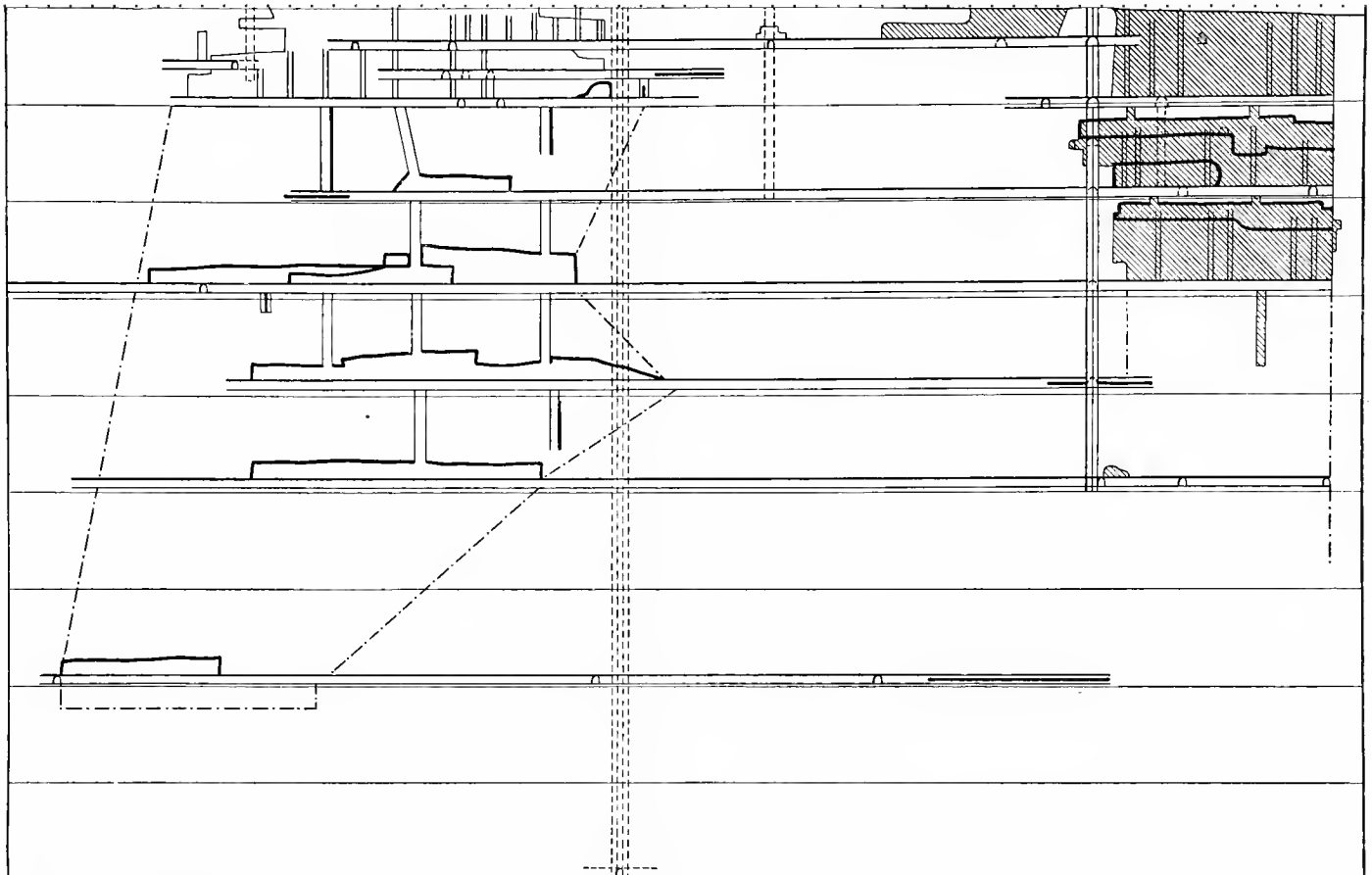


FIG. 79.—Stoping plan of the Ivanhoe mine, Western Australia. Ore-shoots indicated by dotted boundary lines. Report of the Company for the year 1902.

through their auriferous deposits at distances of 100 feet apart, in addition to the more usual horizontal sections. Such vertical sections in the case of the Golden Horseshoe mine are illustrated in Figs. 73–78. From such graphic representations models of the deposits can at once be made, or if the drawings be transferred to glass plates arranged in order and to scale, the most perfect picture is obtained.

Carefully kept plans however do not only give all the necessary information concerning the behaviour of the ore-body in strike and in dip, but also contain data connected with the distribution of the metal content. When describing later the method of taking samples it will be explained that the assay results should be entered upon the mine plans at the places where the samples were taken, because in this way only is it possible to recognize the richer parts of the deposit and to keep these separate from

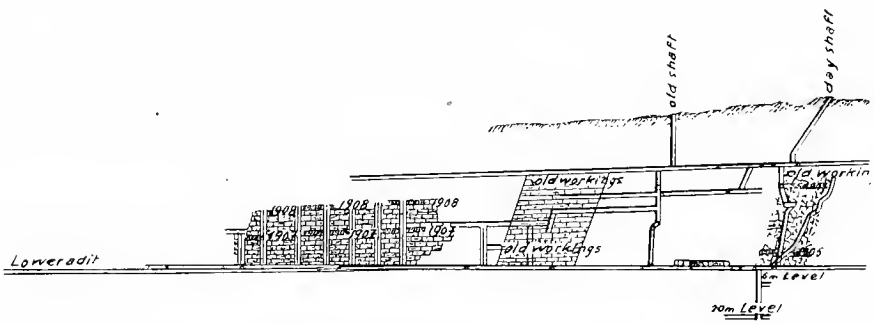


Fig. 81.—Position of stoping at the Goldkaule lead-zinc mine near Wissen on the river Sieg, Germany, indicating the stoping done in the years 1907, 1908. Scale, 1 : 3000.

the others. Where by careful sampling, the 'ore-shoots,' that is to say the richer zones, have been defined, work is naturally confined to these if the intervening portions of the deposit are unpayable. The stoping plan in such cases gives all possible information concerning the extent and number of the ore-shoots, since development and mining work are almost entirely confined to these. If the exhausted areas are carefully entered upon the ground plan of a mine it is even possible under favourable circumstances to be able from the position of these areas to gather the condition of the mine and the prospects of its immediate future. For instance, Fig. 80 is the plan of the Associated Northern Blocks mine, Western Australia, a mine which in former years was widely known on account of its large output of rich gold ore. If the position of the stopes upon this plan be compared with the depth of the levels on which they occur, it will be seen that in this lode, which strikes roughly to the north, the ore is not evenly distributed but forms one especially rich shoot which pitches to the south, in which direction and in depth it passes into the ground of the neighbouring mine.

From the continued advance of stoping in this direction it was possible from this plan to foresee when this rich ore would come to an end. Since in such cases of irregular mining a sudden impoverishment in the ore must follow, the study of mine plans in this connection is of the greatest importance in forming an opinion of any deposit.

The study of ore-deposits does not however only concern itself with the determination of their circumstances in space and their material constitution, but at the same time it provides points of the greatest assistance in the solution of various economic factors among which that of the ore-reserves is the most important. In the correct estimation of this factor the determination of the exhausted areas is of great importance and in making this estimate the stoping plan is more useful than all the others.

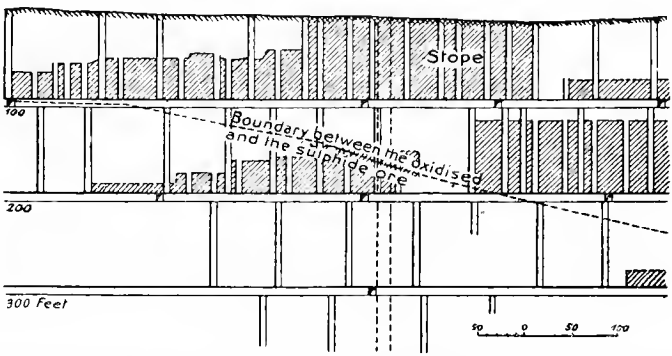


FIG. 82.—Stoping plan of the No. 3 lode, Golden Horseshoe mine, showing the boundary between the oxidized and the sulphide ore. Report of the Company for the year 1902.

Carefully managed mines moreover indicate upon their plans not only the exhausted areas but, as illustrated in Fig. 81, also the areas mined each year. From plans so kept it is possible to form some idea of the life of a mine.

Since generally only those portions of a deposit which are payable are worked, the stoping plan upon which the exhausted areas are entered gives, especially in the cases of those mines which have had a long life, a reliable picture of the relation of the payable to the unpayable portions. In a properly managed mine, development and mining are systematically undertaken; deeper levels are regularly advanced and the ore, if payable, is mined in practically unbroken sequence from the top towards the bottom. If then from a mine plan it is seen for instance that the ore above the first, second, and third levels had been mined; that the ore over the fourth and fifth levels was still standing; while that over the

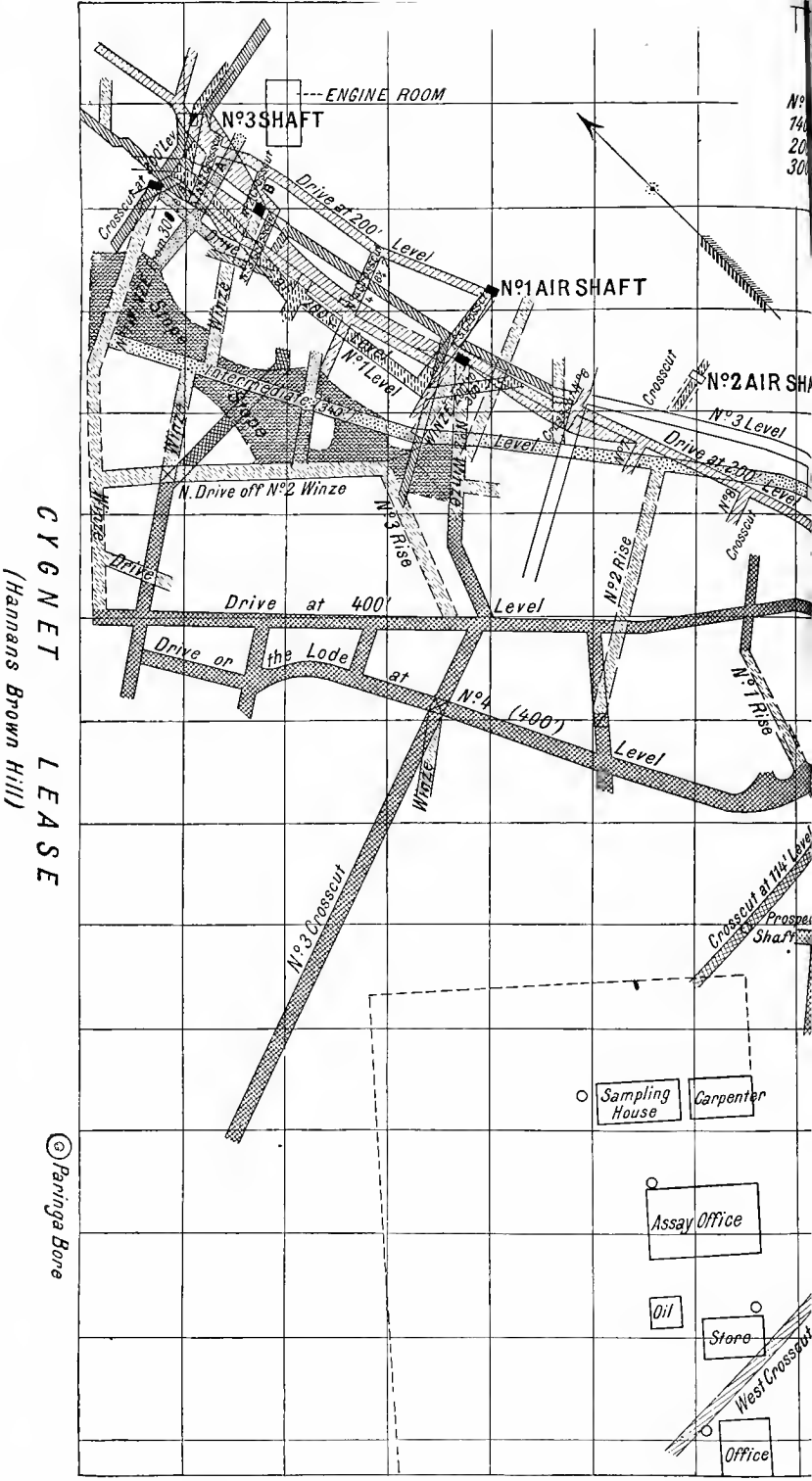
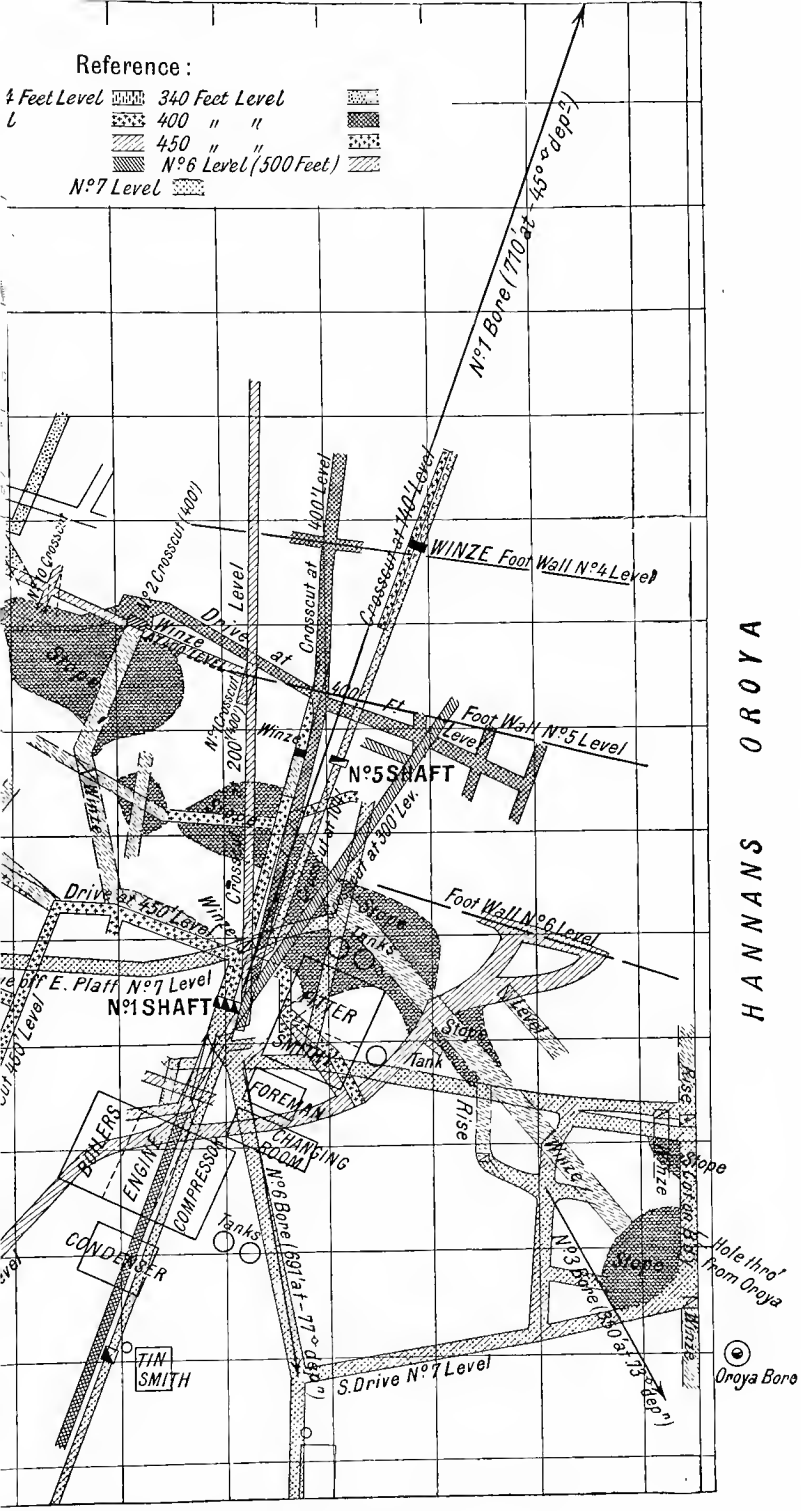


FIG. 80.—Ground plan of the Associated



position of the stopes on the different levels the pitch of the ore-body to the south into the

Scale, 1 : 1080.

sixth was being actively worked, it might with certainty be gathered that the ore above the fourth and fifth was unpayable.

Again, since development work under normal circumstances advances regularly into depth, every succeeding level will at any one time be shorter

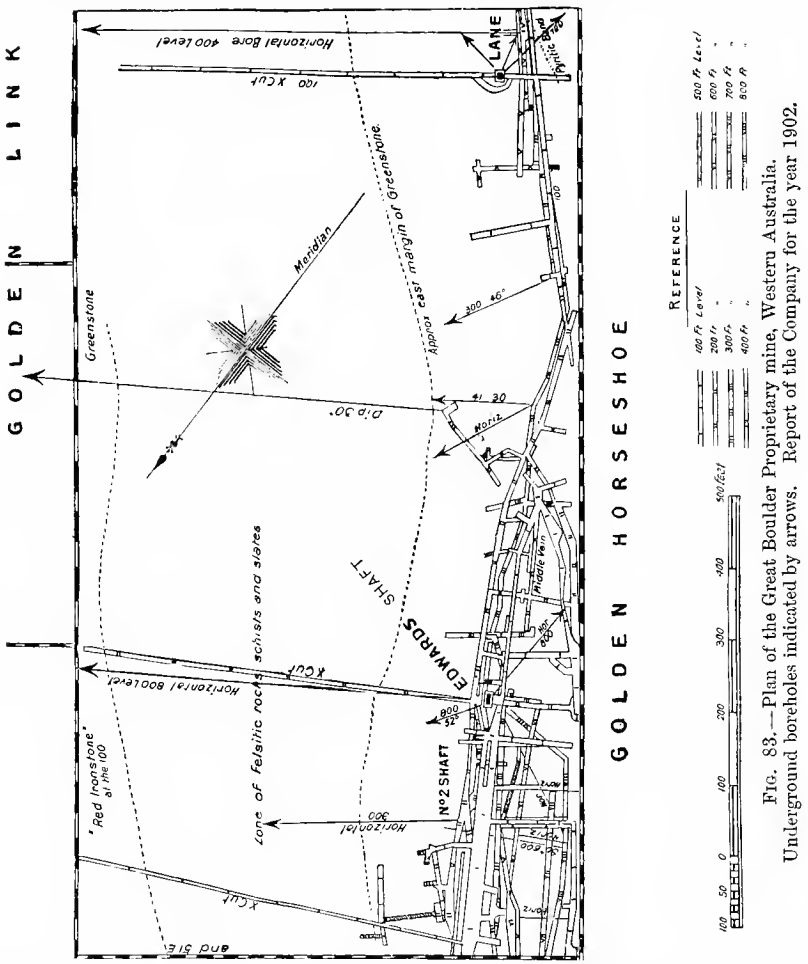


Fig. 83.—Plan of the Great Boulder Proprietary mine, Western Australia. Underground boreholes indicated by arrows. Report of the Company for the year 1902.

than the one above. If therefore it is seen from a plan that below a certain point the levels are approximately of equal length and without any stoping done upon them, it may be taken as certain that the payable ore has pinched out in depth and that new ore-bodies are being eagerly sought. Similarly, mine plans give information concerning the distribution of ore along the strike even though no proper shoots exist. A stoping plan on which unworked areas are surrounded by stopes, indicates that the dis-

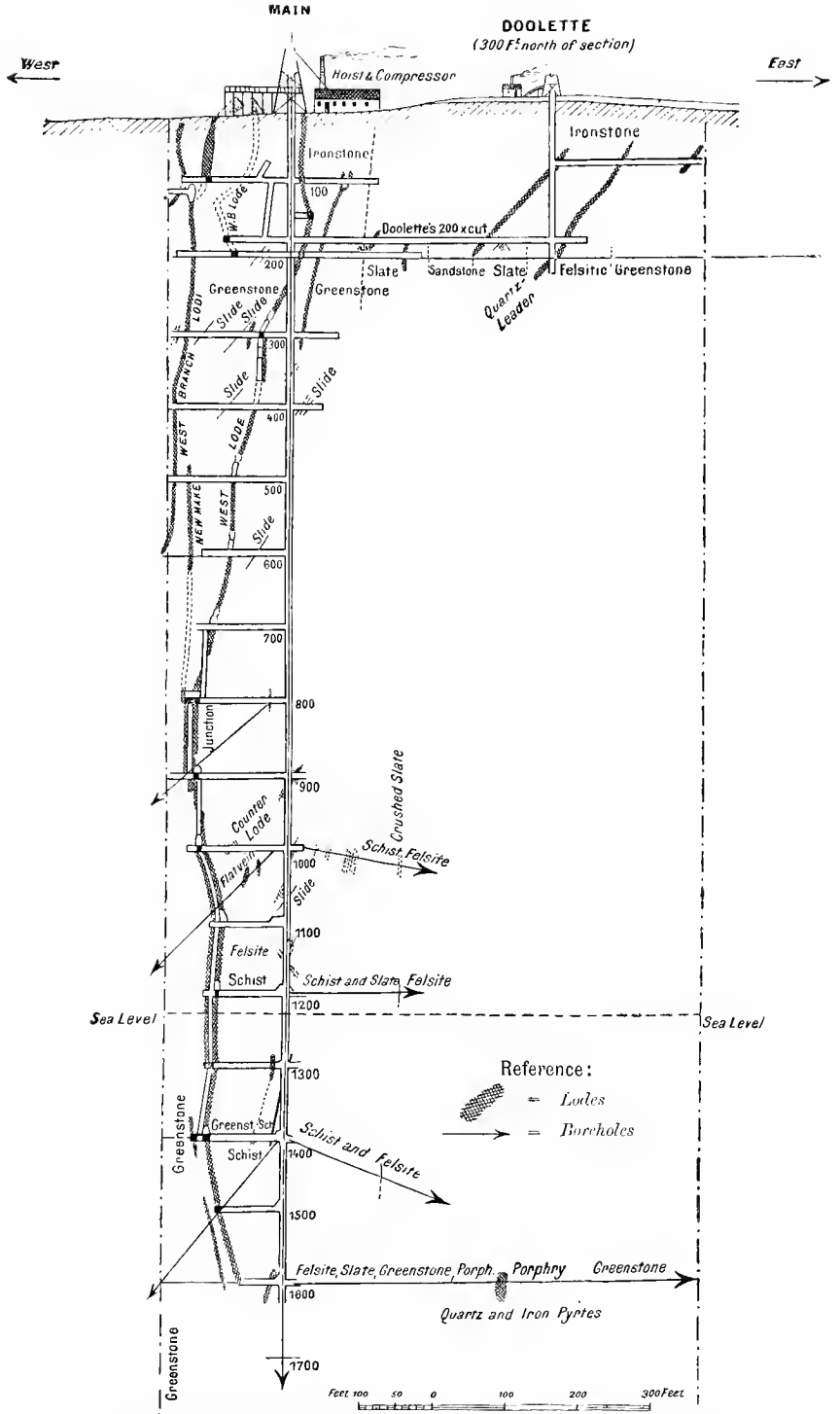


FIG. 84.—Cross section of the Great Boulder, boreholes indicated by arrows. Report of the Company for the year 1902.

tribution of ore along the strike is irregular. This is illustrated in Figs. 80 and 81.

In addition to the details of stoping, plans also usually contain data concerning the width and the metal content of the deposit at different places. It is becoming more and more the custom where the oxidized and sulphide ores are radically different, to mark upon the stoping plan the boundary between these two zones, more particularly as the treatment of the former is often quite different to that suitable for the latter. Such a line of demarcation is indicated in Fig. 82. In those gold mines where for example the gold in the primary zone is associated with tellurium or pyrite while that in the oxidized zone is entirely free, it has become the rule to indicate upon the plans the boundary between the two classes of ore. In the estimation of the ore-reserves consideration is given to this point, and the so-called sulphide ore which requires roasting or the application of bromo-cyanide, is kept separate from the oxidized ore for which amalgamation and ordinary cyanidation are sufficient.

In those mining districts where in the development of any deposit of ore or other mineral extended use is made of horizontal and inclined bore-holes, the mine plans and sections show these holes in addition to the ordinary workings. Since to-day it is possible to drill holes up to 1200 m. in length and at any desired angle without appreciable deflection, a simple arrow along the line of the hole suffices to indicate such a hole, if, on account of the foreshortening which occurs in most projections, this arrow be accompanied by the figures of its length and inclination. Since however core-drilling allows also of the exact determination of the nature of the beds traversed, the most complete representation of such a hole is presented when, in addition, the rock sequence is given in colours along this arrow.

THE MANNER AND CAUSE OF FRACTURE

LITERATURE

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BOTH by actual experiment as well as by observation in the field it has been sought to fathom the causes from which fracture results. Daubrée, in his work on experimental geology, showed that tension and extension, compression and plication, and finally also torsion, come into question. The tectonic fissures resulting from any of these circumstances of stress are formed by forces which have their origin outside the rock in which the

effect is produced. These ' exokinetic ' fissures, which generally occur in connection with orogenic processes, are to be distinguished from those termed ' endokinetic,' which depend upon causes arising within the rock itself. These latter may again be divided into two classes, one due entirely to mechanical causes, while with the other chemical-geological processes are active at the same time.

Tectonic fissures, most of which owe their origin to orogenic forces, may continue to great depth. Whether in particular cases extension or compression were the cause of their formation cannot always be determined. It must also be considered in this connection that every mountain-forming pressure which produces compression in one place, must at some other place upon the earth's crust produce tension. In both cases fissures are formed when and where the elastic limit of the rock is passed.

With plication, that is the thrust to anticlines above and to synclines below, such fissures are known as anticlinal and as synclinal fissures. These from the nature of their formation run more or less at right angles to the direction of the pressure and strike therefore with the strata wherein they occur. Experience shows that in addition in all areas of intense folding a large number of other fissures are found cutting across the strata approximately in the direction of the pressure. While the strike fissures provide opportunity for the formation of ' strike lodes,' those which cut across the strata serve equally for ' cross lodes.' Since generally there occur many more transverse than longitudinal fissures, lodes across the formation are consequently more numerous than those along it. In most cases the cross fissures remain open and serve as channels for the circulation of water and of solutions, while it is by no means invariably the case that dislocation has taken place along them.

Smaller fractures also resulting from compression may, in places and over considerable areas, be so numerous as to produce a complete shattering of the rock which in cases of extreme compression is given the appearance of a mosaic of small angular fragments most of which have striated surfaces indicating considerable internal movement. Excellent examples of this structure are afforded by many of the pyrite bodies of the Rio Tinto district, which district is remarkable for the evidences of intense pressure-metamorphism.

The experience that overthrusts, which are the consequences of extreme plication, rarely ever carry ore, is one of special significance in the study of deposits, since in it lies an essential difference between faults and overthrusts. This fact is connected with the difference in the water circulation in the two cases, and this again may be referred to the mode of formation of the two classes of disturbance; while faults and cross

fissures are often at least partly open, overthrusts are generally friction zones such as impound water.

Although longitudinal and transverse fissures owe both their formation and arrangement to orogenic pressure, no open space can naturally result till after such pressure has come to an end. In this respect, however, an exceptional position is occupied by those fissures which have arisen along bedding-planes in anticlines or synclines. These are best known at Bendigo in Australia, where in anticlines they have been found most regularly one over another. Should mineral solutions enter such spaces, the resulting deposits are either convex or concave, tapering on either hand till they disappear. These are the so-called 'saddle reefs.'

The fissures resulting from tension likewise seldom appear singly, but more generally occur in parallel though occasionally in diverging series. Daubrée and afterwards Kayser rightly pointed out that these tension fissures occur more often than was formerly thought. The sinking of wedge-shaped masses can generally best be explained as the result of tension, though in rarer cases it may be explained by the solution of beds along fissures in such a manner that these beds lose volume and consequently sink into smaller space below. In addition to tension-fissures of small and limited extent, others have been described so large as to constitute the features of a country. Kayser in his well-known text-book mentions the observations by Russian geologists upon such occurrences in Middle and East Siberia, and gives as well their explanation of the Baikal Sea depression by the operation of tension. Richthofen explained the chain of mountainous islands lying off the coast of Eastern Asia as a tension curve, whereas their arrangement was formerly accepted as resulting from horizontal pressure. The difference between the phenomena of fracture produced by tension and those produced by compression is just as difficult of determination on a small scale as it was in this case on a large scale. Finally tension fissures may also form in accidented country when rock masses, owing to defects upon their flanks, weaken and eventually become detached; this, as the land-slides at Odessa show, may even take place to such an extent that step-faulting results.

Torsion fissures are formed when the mass, moving under pressure or tension, encounters resistance on one side or in one place. To Lossen[1] is due the instructive illustration afforded by the shattering of a window-pane when this is turned and twisted about a point, as for instance at the opening of the window with one corner, upper or lower, held fast. Such fractures, which in bunches diverge radially from the turning-point, may be accompanied by curved diagonal fractures.

When the cause of fracture lies in the nature of the rock itself, endo-

[1] *Jahrb. d. Preuss. Geol. Landesanst.*, 1886.

kinetic fracture, the types enumerated below may be differentiated. In hot dry weather, and in consequence of the contraction due to drying, sun-cracks are formed on the surface of such sediments as clay or mud; a bed deposited later and filling these cracks would therefore show on its lower side a net-work negative. Such cracks and negatives as these have, as far as present experience goes, no importance in relation to ore-deposits. Similarly when originally damp sediments become dry, a jointed structure arises similar to that to be observed as the result of the cooling of eruptive rocks. With these latter the fractures so resulting are known as 'contraction joints.' These are often difficult to recognize in undecomposed rock, though they show themselves plainly when the rock is broken or becomes weathered. Such joints may also appear, both in eruptive and in sedimentary rocks, as secondary effects resulting from pressure, tension, and torsion; when so formed they are known as ordinary or 'simple joints.' Only those types will however here be considered which are the result of contraction in eruptive rocks or more rarely in sediments. Of these Kayser differentiates the following:

(*a*) Irregular polyhedral jointing, in which the rock-mass breaks into differently shaped, sharp-sided, and angular pieces.—Porphyry and diabase among eruptive rocks; and grauwacke, limestone, and quartzite among sedimentary rocks, tend to this form of jointing. The irregular veins, representative of polyhedral jointing, which often traverse stanniferous granite are important to the student of deposits. Such veins, occasionally containing cassiterite and associated minerals, traverse the granite in all directions, forming with the impregnated zones which accompany them the so-called 'stockworks' from which considerable quantities of ore have been obtained.

(*b*) Tabular jointing, in which the rock appears in parallel slabs or plates which generally are flat but which in rarer cases may be gently curved. Numerous cases are known where joints in eruptive rocks must be referred to differences in tension set up at the solidification of the magma in a direction perpendicular to the cooling surface. Such tabular jointing is the more striking the quicker the cooling was effected, consequently it is best seen in the outside and more quickly solidified portion of an eruptive mass; in the case of eruptive flows therefore chiefly in the neighbourhood of the upper surface, and with dykes in the neighbourhood of the walls. It is seldom seen right inside a rock-mass. When the slabs are very thick, as is often the case with granite, the occurrence is described as block jointing; when they are very thin the structure approaches that of slate, this occurring with phonolite, trachyte, quartz-porphyry, and basalt.

Tabular jointing in relation to ore-deposits is important in the case

of the granite of Zinnwald where contraction fissures approximately parallel to the surface and having in part considerable thickness, are filled with cassiterite, its associates, and other lodestuff. The fracturing forces here were so great that these fissures, roughly of watch-glass shape, do not confine themselves to the granite but continue into the adjoining sediments.

(*c*) Prismatic or columnar jointing, in which the rock is divided into regular prisms or columns.—This form is especially frequent with basalt. It likewise is an effect of cooling which, starting from the exposed surface, continued ever deeper into the interior. The columns often of hexagonal form are usually arranged at right angles to the cooling surface, so that in ordinary masses the arrangement is concentric and radiating whereas in dykes it is parallel to the walls. This form of jointing is without importance in relation to ore-deposits.

(*d*) Spheroidal jointing, in which during cooling the rock contracted around a centre so that successive curved or spherical shells resulted.—This form is not infrequently accompanied by columnar jointing. It occurs with basalt, diabase, melaphyre, trachyte, porphyry, and less markedly with diorite, syenite, and gabbro. In close connection with this jointing there exists also an irregular spheroidal form, in which the rock-mass falls into large spheroids which have variously barrel, roller, pillow, or tubular shape. This form of jointing has however no importance in relation to ore-deposits.

(*e*) Cylindrical jointing.—This is seldom seen. It occurs with the andesite of the Stenzelberg in the Siebengebirge, the mass of which rock is built up of cylinders which separate in successive concentric shells.

(*f*) Quadrangular jointing, in which when fully developed, three systems of joints cut one another at right angles.—This form, which occurs in eruptive as well as in sedimentary rocks, is well illustrated by the block weathering of many granites and the right-angled jointing of the Quadersandstein in the Saxon-Bohemian mountains. Closely related to it are the ' ladder lodes ' of Beresowsk in the Urals and of several places in Telemarken, which have arisen when transverse fractures formed in the cooling mass of an eruptive dyke later became filled with ore ; as these fractures are often connected with one another by others running parallel to the walls the name given to the whole occurrence is appropriate.

There exists as a special kind of contact effect a characteristic fracturing of sediments when in the near neighbourhood of eruptive rocks. When such sediments are easily affected by eruptive contact they often exhibit columnar jointing.

Chemical-geological alterations depend upon the two following essential factors : (1) the chemical composition of the rock, a property which lies

entirely in the rock itself and is therefore endokinetic; and (2) certain effects which can be produced on the rock from outside and which are therefore exokinetic. Fractures due to chemical-geological processes occupy therefore a position intermediate between those due to jointing, the causes of which lie entirely in the rock itself, and those due to orogenic forces, the causes of which lie entirely outside the rock. When for instance anhydrite by the absorption of water becomes gypsum, an increase of volume takes place sufficient to lift and disrupt any rock lying above; pressure so resulting is undoubtedly one cause of the formation of folds and fissures. With alkali beds another cause exists in the possible recrystallization of some of the salts, the newer forms often requiring more space; a mass undergoing such a change can exert tremendous pressure.

In some cases it is not possible to decide whether fractures are due to pressure resulting from the absorption of a new constituent, as for instance water, or to the removal of a constituent during decomposition. The veins of magnesite and of garnierite in serpentine may be regarded in greater part as the fillings of crevices due to such a removal of material. In any case, from the appearance of the red rock in which such veins are found at Frankenstein in Silesia for instance, it is justifiable to conclude that all the constituents of an original serpentine or peridotite had there been leached and a siliceous substance deposited in their place. In New Caledonia also, where the origin of the garnierite veins is referred to surface weathering, the fractures are due to removal of material by chemical-geological means. In this connection the formation of the small auriferous veins in the bed-rock below gravel-deposits is not without interest; the action of running water causes a large number of little crevices to be formed which afterwards become filled from solutions taking their gold content from the auriferous gravel. An analogous formation of fractures is seen in the case of laterite; during decomposition of the rocks coming to the surface, cracks are formed in which iron ore becomes deposited and from which the brown colour characteristic of laterization gradually diminishes.

Fractures formed in this manner play also a considerable part in the phenomena of secondary variation in depth. By the various chemical-geological processes active in the upper portions of deposits, numerous crevices referable in part to increase in volume and in part to removal of material, are formed. While in the oxidation zone these are more often filled with limonite and other secondary oxidation ores or with native metals, in the cementation zone they generally carry rich sulphides, and from them the further alteration of the original ore proceeds by metasomatis. Such veins carrying cementation ore penetrate right into the primary zone.

With such fractures as these, which owe their origin to aqueous activity, those also must be reckoned which, existing first as narrow cracks or bedding-planes in a soluble rock, become afterwards considerably enlarged by circulating water. In such cases the occurrence is not always exclusively chemical, there may also be a mechanical removal by the water; it is in fact generally the case that with the actual chemical process mechanical alteration of the rock also plays a great part.

Caving fractures arise when within the earth's crust beds easily dissolved are removed by circulating water. The roof of the cavity thus formed collapses as soon as the limit of elasticity is passed and cracks and crevices result. Rock-salt, potassium salts, gypsum, and anhydrite, are easily dissolved in this manner. A very interesting occurrence of this description is presented at Raesfeld and Rhade in northern Westphalia, near the boundary with Holland. In that district the rock-salt of the Upper Zechstein has been leached causing the Bunter sandstone and the Cretaceous above to cave or collapse. Not infrequently some of the fractures so resulting are found filled with pyrite. At the present day, fractures similar to these are being formed in the course of mining operations when beds collapse into exhausted spaces. When this occurs experience shows that this manner of fracture, apart from the settlement of the hanging-wall whereby an area of subsidence bounded by the angle of rupture is produced, conforms to laws not only dependent upon the situation of the exhausted space but also upon the structure and bedding of the rocks above it, while in addition the dip of the beds plays an important part. These factors in the end cause the rupture to disappear in the overlying beds. The extension of such caving fractures depends greatly upon the character of the rocks in the hanging-wall and the shape of the cavity. Where large areas of uniform thickness are removed either by natural agencies or by mining and the rocks above possess sufficient elasticity these may gradually bend and no fracture of any importance need be formed.

The Duration of Fracture and the Age of Lodes.—It has repeatedly been pointed out that the age of a lode is not identical with that of the fissure in which it occurs and that the actual formation of the fracture as well as the later filling may both be quite complex processes. The movements along fissures often belong to the most varied geological epochs. Geological investigation on the left bank of the lower Rhine has shown that the fractures in that district were first rent towards the close of the Carboniferous period when also a subsidence of the beds in the hanging-wall occurred. Since then tectonic movements have repeatedly taken place along the fissures then formed, and faulting in Diluvial landscape can be traced most plainly, that is to say, the last movements

took place but a relatively short time ago, or in any case after the deposition of the Diluvial beds. This investigation also showed that it is more than probable that along many of the faults in the Coal formation, which faults farther to the south around Velbert and Aachen in part occur as lodes, movement is still taking place.

Similar phenomena are also evidenced in the material of many lodes. Should, along a fissure which became filled shortly after its formation, a second movement take place, there is generally evidence of this in the structure of the filling; if into such new fissure mineral solutions find their way a younger lode becomes formed within the older. Among many others a very good example of such an occurrence is afforded by the Siglitz lode in the Tauern, where a younger lode of auriferous arsenical pyrite was recognized by Krusch to occur in an older lode of auriferous pyrite. In general, the material of which a lode consists depends a good deal upon the length of time it took to form. Naturally each later mineral solution entering a fissure is in the position gradually to displace the material already there, till finally a lode might result having nothing in common with the material of the first filling.

The age of the actual fracture, the time occupied in its formation, and the varying age of the eventual filling, are the three factors which together constitute the age of a lode.

Nomenclature of Cavity-Fillings.[1]—The terms often used in English for the different forms of lodes and chamber-deposits require some further description.

The term 'vein,' as often used by American writers, is much more inclusive than the German expression '*Gang*,' and it is consequently applied in many cases where the German expression could not be used. Under the term 'chambered veins' is understood such deposits in an insoluble country-rock as at places along their extent show large bulges; according to G. F. Becker these probably originated after the formation of the fracture by the caving of the country-rock at particular places where it had previously been shattered by torsion. 'Gash veins' are formed by the solvent action of water along bedding-planes and transverse fractures; they have rarely any great length, and as they are generally found in limestone and dolomite they belong in greater part to the metasomatic deposits, that is either to the lead-zinc or to the siderite occurrences.

'Pipe veins' are sometimes mentioned in English and American literature. These in all cases are chimney or columnar deposits standing more or less vertically. The expression is not only used for deposits in limestone but for others, such for instance as the tin occurrences recently

[1] See Preface.

found in South Africa, which are inclined similarly to but flatter than the diamantiferous pipes. 'Flats' differing from pipes follow the bedding of the formation in which they are found and are limited to occurrences in limestone.

The term 'contact lode' requires special mention. Many authorities apply it to such lode-like occurrences as appear at the contact of an eruptive with a sedimentary rock, and which therefore are the fillings of spaces which might well have arisen from fracturing along such a line, or from the action of water using this line of weakness as its channel and gradually removing portions of the walls. They might also even be contraction fractures formed, like those at Beresowsk, at the periphery of an eruptive rock when cooling. Since the use of the expression 'contact metamorphic deposits,' or more shortly 'contact deposits,' became general, the expression 'contact' is only properly applied to such occurrences as through contact metamorphism are closely associated with eruptive phenomena. It is everywhere acknowledged that true contact deposits may closely resemble lodes. Such would be the case when any fissure standing open in the contact zone, or becoming formed there by contact metamorphism, later became filled with ore deposited from solutions issuing from the magma. On these grounds the limitation of the term 'contact lode' to lode-like deposits of contact metamorphic origin is strongly to be recommended.

The Arrangement of Lode Fissures.—It has already been explained that in general the fracturing forces at work form either irregular fractures with ever changing strike and dip, or simple fissures maintaining a definite course for a considerable distance. In the first case the result would be, for example, a 'stockwork,' or when the veins were not too irregular a 'network.' Experience shows however that even with the larger lodes it is seldom that only one fissure is formed, but that in most cases several are produced to form a 'lode-system' or a 'lode-series.' When it is said for instance that the Mother Lode of California has an extension of more than one hundred kilometres along the strike, it is not meant that the same single fissure occurs over all that length, but that the lode consists of a number of fissures having the same strike, of which when one gives out there is another not far away in the hanging- or the foot-wall to take its place. It is therefore advisable when one of the larger lodes pinches out to continue a short distance in the same direction, and then to crosscut right and left in order to cut any new lode possibly present.

Occasionally also a number of fractures with various strikes may be found close together in a 'swarm'; such an occurrence is often to be seen in Siegerland. According to Denckmann, these are found when the out-

side fissures of a tectonic depression are connected by a large number of others running diagonally and transversely.

The fact that lodes are more frequently found in the neighbourhood of important tectonic lines has been particularly brought out by the geological survey of the Rhine *Schiefergebirge* undertaken by the *Preussischen Geologischen Landesanstalt.* At the formation of a tectonic fissure a large number of transverse fissures may arise, which, if they are parallel, become 'parallel lodes.' Such lodes also often agree with one another in dip and, when they are accompanied by faulting, usually show step-faulting. The fact of being parallel however is not sufficient to establish contemporaneity; since fracture in general takes the line of least resistance, the same districts may have suffered at different times. When fissures proceed out from a centre, as might happen when torsion played the greater part, they give rise to 'radial lodes.'

The Behaviour of Lodes to One Another.—When lodes of different age occur together the older may influence the strike of the younger or *vice versa.* Under the term 'lode junction' is understood the situation where two lodes striking in different directions intersect one another. If the angle of intersection be a right angle the junction is spoken of as a 'square junction,' but if it be an acute angle then the term 'oblique junction' is used. With lodes of the same strike, a junction can only occur if the lodes dip towards one another when the intersection is spoken of as a 'dip junction.'

The term 'deviation' in connection with lodes is used when the line taken by a later fissure is influenced by one already existing, in such a manner that the more recent one follows the other for a time and afterwards leaves it, without having crossed it.

In all these cases the lodes as a rule are of different age although it does occur that intersecting lodes are occasionally contemporaneous. Even however when such contemporaneity can be established for the filling, it is in no sense established that the fractures are equally contemporaneous. Deviation is to be distinguished from 'deflection' in which the deflected portion may continue beyond the obstacle, either as a simple fissure or as a veined zone. With such deflection not only may pre-existing fissures be the cause but friction zones and overthrusts, which as before mentioned hardly ever in themselves contain any ore, may serve equally, bringing about deflection by the difference between them and the normal country-rock.

MINERAL CONTENT OF ORE-DEPOSITS

Ore-deposits contain the following different components, which may occur in every structural arrangement and in every possible proportion.

1. Ore.
2. Gangue.
3. Rock inclusions.

I. The Ore

In relation to ore-deposits, any metalliferous mass from the like of which in the present state of the arts of mining, ore-dressing, and metallurgy, a metal or metal compound may in general be produced on a large scale and with profit, constitutes an ore. The term is not one of chemical technology and accordingly such compounds, as for instance the potassium salts, are not included. This definition, it is seen, differs essentially from that understood by mineralogists who regard ores as minerals containing metals in certain fixed combinations. In the study of ore-deposits, on the other hand, the mineral masses and rocks included as ore contain a lower percentage of ore in the mineralogical sense, the higher the value of the metal concerned. In mineralogy for instance auriferous pyrite is a gold ore, while in the study of ore-deposits the quartz masses which may contain this pyrite in such quantity that a profitable extraction of the gold under present metallurgical conditions is possible, constitute the ore, though in such a case only the smallest fraction of the mass is valuable.

The term in this sense does not however coincide with that of payability. It only demands that, without considering the conditions of communication or the quantity present at any particular place of discovery, such mineral matter in general is being applied under present conditions with profit and on a large scale to the production of metal. A mass of ore is however only payable when it occurs both in the necessary quantity and under those economic conditions which permit a profit. For instance a hæmatite lode in Germany, 5 cm. thick, is without question ore in the

sense of the study of deposits because in the present position of the arts it is certainly possible to produce iron on a large scale and with profit from hæmatite. Such a deposit of iron ore would however not be payable because with the means at present available to the miner, the quantity is too small to permit a profitable extraction even under the favourable conditions of communication which exist in Germany. Similarly, a mountain of magnetite in the centre of Africa would rightly be regarded as ore because the smelting of magnetite on a large scale and with profit is in general possible. Yet, however great the quantity, such a deposit

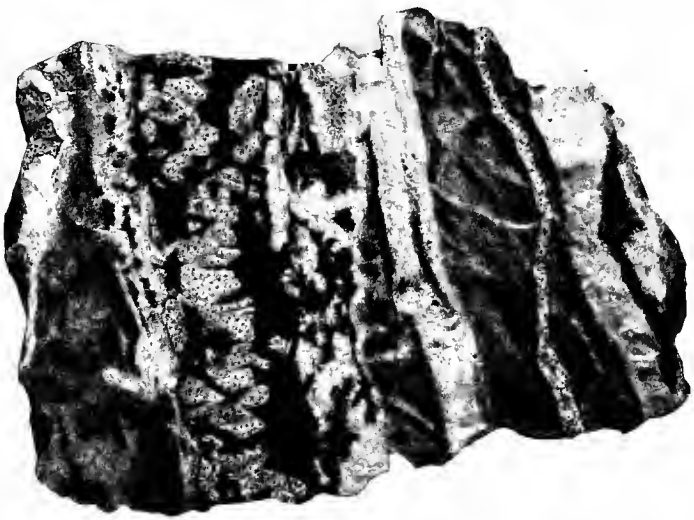

FIG. 85.—Lode-filling at Mitterberg near Bischofshofen, Salzburg, consisting of chalcopyrite (black), representing the ore ; quartz (white) and siderite (white with black dots), representing the gangue ; and dark slate (light to dark-grey), representing the rock-inclusions. Krusch, *Unt. u. Bew. v. Erzl.* p. 5.

would nevertheless not fulfil the conditions of payability because on account of its situation it would be utterly impossible to deliver it to a smelting works at a profit.

The claim that from ore it must be possible to produce metals or metal compounds on a large scale and with profit, postulates a certain minimum metal content. Material containing 15 per cent of iron cannot, in however great an accumulation, be regarded as ore, because it is not possible by any known metallurgical processes to produce iron at a profit from such a mass without the addition of richer material ; there should be at least sufficient iron present not only to cover the costs of ore-dressing and of metallurgical treatment but to leave something over. The lower limit permissible for the metal content will differ somewhat for each producing district. It may be taken that in Germany, under present conditions, iron

ores must contain at least 25 per cent of iron before they can be reckoned as ores of that metal. If in the future magnetic separation should develop materially, such an advance would be of deciding importance to this lower limit of content in iron ore. From this it will be realized that the conception of the term 'ore' is dependent upon the position of the arts of ore-dressing and metallurgy and that, speaking generally, the lower limit of metal content will sink lower and lower with the development of technical processes. In consequence poorer and poorer masses will come to be included as ore.

So long as the production of zinc from sphalerite was not understood that mineral was not an ore in the sense here described, though to-day, when the metallurgy of zinc has been perfected, it is the ore most sought. Similarly, so long as nickel and cobalt minerals could not be applied to the manufacture of nickel and cobalt compounds on a large scale, they were not ores, though to-day they are. It follows therefore that the ores, in their number also, are variable and dependent upon the progress of metallurgy.

The definition here given avoids in the first place the expression 'heavy metals' which, since more than one light metal is now produced on a large scale, is no longer apt. Bauxite and cryolite, the minerals from which metallic aluminium is produced, are consequently important aluminium ores.

Further, to satisfy this conception of the term it is not necessary that a metal proper should be produced. There exist a large number of metals for which when in the metallic form there is little or no use while, on the other hand, certain compounds, usually won as intermediate products, are particularly sought. For example, from cobalt ores it is not sought to produce metallic cobalt but the oxide or some other combination. The material treated must, nevertheless, without question be considered as ore.

Among ores siderite takes a special place, being sometimes regarded as ore and sometimes as gangue. It is regarded as ore in all iron deposits and in all deposits where, occurring with other ores, it is worked for the iron it contains. On the other hand, when it occupies a subordinate place in deposits worked for other ores from which in breaking it cannot be kept separate, it is not ore but gangue.

Sulphur-, alum-, and vitriol ores, among others, fall outside the scope of the above definition. Sulphur ores are those sulphur-bearing masses from which sulphur or sulphuric acid can be produced on a large scale and with profit. They include pyrite or marcasite as well as native sulphur and rock more or less impregnated with that element. Since after the sulphuric acid has been won from pyrite the roasted residue may be smelted, this sulphur ore may also be regarded as an iron ore. The alum

ores were used formerly for the production of alum, that is the double sulphate of aluminium and the alkalies. If for instance a slate or a clay in which sufficieut aluminium or alkali be present, contain a certain quantity of pyrite or marcasite, then during weathering the double sulphate will be formed, which can be leached with water. From such a resultant solution either with or without the addition of alkali sulphates, alum may be caused to crystallize. Vitriol ores are those mineral or rock masses from which, by simple means, sulphuric acid or ferrous sulphate may be profitably produced. To this group belong peat and lignite containing much pyrite or marcasite, and also those rocks which are impregnated with these minerals and from which as the result of the abovementioned weathering, ferric sulphate may be leached. Sometimes also peat contains sufficient free sulphuric acid to allow it to be classed with these vitriol ores. Alum- and vitriol ores are now in their industrial importance but of historical interest, and in any case they concern the chemical rather than the metallurgical industry.

The lower the value of the metal concerned the higher will be the minimum metal content. In the case of iron a minimum of 25 per cent, that is 250 kg. per metric ton, is regarded as the lower limit in Germany. With gold ores 5 grm. per ton suffices under favourable circumstances not only to satisfy the definition of ore, but under conditions similar to those existing in Germany to render a primary auriferous deposit payable. Similarly a gravel-deposit needs only to contain a fraction of a gramme per ton in order to constitute, other conditions being favourable, a very valuable gold ore.

Ferruginous masses whose metal content is too low to allow iron to be won from them on a large scale and with profit, may nevertheless be applied as fluxes when they contain certain material, such for instance as lime, which is necessary for the smelting of other and richer ores. These fluxes therefore play a considerable part in the metallurgy of iron. Where for example iron ore has been formed by the replacement of limestone, or where a sedimentary ferruginous bed passes gradually over to a rock rich in lime, it is usual to find that, in addition to the reserves of iron ore, a large quantity of this ferruginous flux is present, of which, when estimating the metallic iron in reserve, account must be taken.

The question of late years whether vivianite, the phosphate of iron, was to be reckoned as an iron ore, has been answered in the affirmative by the Prussian authorities. There can be no doubt however that vivianite does not fulfil the conditions imposed by the study of ore-deposits since, on account of the large amount of phosphorus contained, it is not possible to produce iron on a large scale and with profit from it alone. This decision concerning vivianite has therefore not been made from the point of view taken

in the study of deposits, but entirely from that of the mining law. When this mineral occurs in large masses it is in consequence of its phosphorus-content of some importance in the 'Thomas' process, whereby it finds itself so closely connected with bog iron ore that its exclusion by the law from the number of iron ores might cause serious legal difficulty. In those countries where bog ore belongs to the owner of the surface, and this is generally the case, the question of the legal position of vivianite is of no importance.

The lists of ores usually found in text-books, give generally a simple enumeration of the various minerals without any indication of their significance in the examination and the valuation of ore-deposits. This significance depends not only upon quantity but also upon regular occurrence in those defined depth-zones which result from the processes of decomposition and in the formation of which the level of the ground-water plays an important part. With steeply inclined deposits atmospheric water finding its way to a mass of ore into which it sinks, causes a re-arrangement of the originally evenly distributed ore content in such a manner that, where a complete profile of this mass still exists, there arises near the surface an oxidation zone, below this an enriched or cementation zone, and then in greater depth the zone of primary ore. Considering only the relative amount of the secondary and altered ore to the primary and unaltered, the latter generally predominates, while it is further distinguished from the two secondary zones by a fairly uniform or at least definitely arranged distribution of its metal content. In these two zones the migration of the metals occasioned by chemical-geological processes is such that in the cementation zone, which is comparatively thin, the metal content often of hundreds of metres becomes collected, and the amount of metal in a unit of height, say of one metre, in this zone is consequently disproportionately greater than in the primary zone.

The manner in which such atmospheric water brings about the phenomena of decomposition is discussed in the chapter dealing with the secondary depth-zones. To appreciate the significance of different ores it is sufficient at this stage to mention the following points.

Like primary ores under like conditions exhibit the same phenomena of decomposition even though the genesis of the original ores may be different. In the process of decomposition effected by the action of the oxygen and the alkali chlorides of meteoric water, oxides, carbonates, sulphates, chlorides, and more seldom bromides and iodides, of the heavy metals, all of which are characteristic of the oxidation zone of an ore-deposit, are first formed. Since usually a large portion of the original metal content of the oxidation zone becomes removed in solution to greater depth and only a relatively small portion in the form of oxides, etc., becomes precipitated, this zone is usually poorer than the primary

zone in so far as gold, silver, copper, zinc, and some other heavy metals, are concerned. This metal in solution, after complete exhaustion of the oxygen and in consequence of precipitation by reduction, accumulates in the underlying cementation zone which usually contains rich sulphides and, comparatively speaking, large accumulations of noble metals. Although, as will be mentioned later, the oxidation and cementation zones usually found with steep ore-deposits do not of necessity always occur, and with some ores, magnetite for instance, are generally completely absent, it is nevertheless necessary when making a valuation of any ore exposure to be clear concerning the zone in which such exposure occurs.

Many metals have indicator ores for the separate zones and in consequence, when enumerating the ores, it is of importance to specify those which are characteristic of the different zones and to state the conclusions which the appearance of such ores allows to be drawn relative to possible change in the metal content in depth.

1. *Gold Ores.*

Ores.	Chemical Composition.	Percentage of Gold contained.
Auriferous pyrite, chaleopyrite, arsenopyrite, stibnite . .	...	Variable
Native gold	Au	40 – 99 (with silver, iron, copper, bismuth)
Calaverite } light telluride ores	$(AuAg)Te_2$	39·5 Au 3·1 Ag
Sylvanite } light telluride ores	$(AuAg)Te_4$	24·2 Au 13·3 Ag
Krennerite } light telluride ores	$(AuAg)Te_2$	39·5 Au 3·1 Ag
Petzite } dark telluride ores	$(AuAg)_2Te$	25·4 Au 41·8 Ag
Nagyagite } dark telluride ores	$Pb_xAu_y(TeSbS)_z$	6 – 13 Au
Selenium gold	Formula unknown	...

The most important primary gold ore is undoubtedly auriferous pyrite, that is a mineral in which the noble metal only occurs as an accessory. Gold is also found associated in an analogous manner with arsenopyrite, stibnite, and chalcopyrite, though not with the same frequency or to the same extent. These ores which in their outward appearance betray nothing of their gold-content, may be termed possible gold ores; whenever found in any new district they should always be assayed. The three first-named are as a rule primary, that is to say they continue below the level of the ground-water though often with lower gold content. Auriferous chalcopyrite may also be primary but is more often found in the cementation zone of gold and copper deposits. Auriferous pyrite, arsenopyrite, and stibnite may also, immediately above the ground-water, similarly contain secondary gold in considerable amount although they themselves be

primary. In such cases the primary ore, viewed macroscopically, differs from the cementation ore only in the matter of its gold content; in greater depth the primary ore contains only primary gold whereas in the enriched zone it contains both primary and secondary gold.

Native Gold.—This occurs in all auriferous deposits of whatever genesis and whether they be primary or secondary. Great accumulations are often secondary and typical of the cementation zone. Primary gold is found :—

(*a*) As the only gold ore present, and sometimes in considerable amount, in gravel-deposits.

(*b*) With auriferous pyrite in lodes and ore-beds.

(*c*) With gold tellurides in lodes which though generally small individually may, when accompanied by an impregnated zone, possess considerable width.

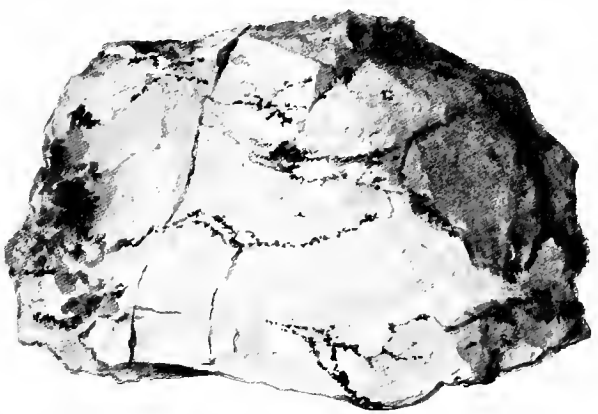

Fig. 86.—Free gold (black), cementing cracks in quartz partly coloured by limonite. Earlton Leases, Mount Margaret River. Collection, *Geol. Landesanst.*, Berlin.

In the case of gravel-deposits, neglecting the unimportant recent deposition which generally makes itself evident in crystal faces, there is obviously no separation of the ore into primary and secondary. With other deposits carrying auriferous pyrite and gold tellurides this separation however becomes more important. When the complete section of one of these deposits still exists, under a poor oxidation zone which carries gold sparingly in cracks filled with limonite or hæmatite, such ores show a cementation zone which often has a very high gold content even though the primary deposit be poor. The gold in this enriched zone, as illustrated in Fig. 86, always occurs filling cracks and irregular spaces. This mode of occurrence, which is particularly to be seen when the sample is made wet, is so characteristic that it establishes a derivation from the

cementation zone even when there is little iron oxide present, and without exception as far as present experience goes it is indicative of the cementation zone of any auriferous deposit concerned. It may also plainly be recognized even in those exceptional cases where the primary deposit itself carries much free gold. The difference between the occurrence of the gold in the primary and that in the cementation zone therefore is not based solely upon quantity but also upon appearance.

FIG. 87.—Free gold (*a*), calaverite (*b*), copper ore (*c*), and petzite (*d*), from the Lake View Mine Kalgoorlie. Collection, *Geol. Landesanst.*, Berlin.

Since in the primary zone the quantity of ore is large while the gold content is low, whereas in the cementation zone the reverse is the case, the determination of the genesis of the free gold is of the greatest importance in making a valuation of any deposit. Confusion in this matter by young engineers and laymen has often enough caused a rich secondary deposit, such as would soon give out in depth, to be regarded as an unusually rich primary occurrence which might be expected to continue.

The telluride gold ores, calaverite, sylvanite, krennerite, petzite, and nagyagite, form a group the members of which so often occur in association with auriferous pyrite that in some districts the miners speak of them simply as sulphide ores. On account of their dull appearance they are, as is to be gathered from Fig. 87, at first not easy to recognize or to distinguish from one another. The number of these compounds of tellurium and gold given in text-books has latterly been decreased because of the discovery that both kalgoorlite and coolgardite were mechanical mixtures in which the characteristic mercury content was due to the presence of coloradoite, the telluride of mercury. Since that discovery such compounds of mercury, tellurium, and gold, are no longer considered to exist.[1] As the gold tellurides are generally quite dull in appearance and greatly resemble other minerals encountered every day, such for instance as

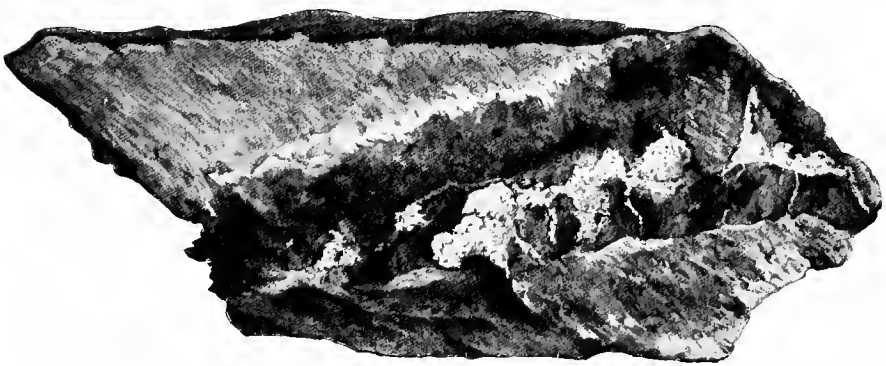

FIG. 88.—Free gold (white), earthy and of a dull-brown colour, along fractures in the oxidation zone of a telluride lode in the Boulder North Extended, Kalgoorlie. Collection, *Geol. Landesanst.*, Berlin.

chalcopyrite, it is necessary to have at hand some method of quickly recognizing them. If a small portion of powdered material in which tellurium is suspected, be placed upon a white porcelain plate and then be brought into contact with a drop of hot sulphuric acid placed near it, this acid along the line of contact will assume a violet colour similar to that of permanganate of potash in solution. With those ores however which surrender their tellurium less readily, it is necessary to apply heat and concentrated acid, which is best done on the clean cover of a porcelain crucible. To determine whether a telluride ore is auriferous, is quickest done on charcoal with the blowpipe. Since, as seen from the table on p. 80, all such ores contain silver, a gold-silver button remains which, when not more than 1 part of gold is present to 3 of silver, may be treated with nitric acid for the separation of the gold.

[1] Spencer, L. J., *Mineralogical Magazine*, February 1903.

Telluride

	Formula.	Theoretical Composition.	Results of Analyses.
A. Light-coloured Ores—			
Calaverite . . . . (the most frequent)	$(Au, Ag)Te_2$	57·4 Te 39·5 Au 3·1 Ag	54·0–60·3 Te 33·9–44·0 Au Tr– 4·8 Ag
Sylvanite . . . . (comparatively rare)	$AuAgTe_4$	62·5 Te 24·2 Au 13·3 Ag	60·45–60·83 Te 28·5 –29·8 Au 9·1 – 9·7 Ag
Krennerite . . . . (comparatively rare)	$(Au, Ag)Te_2$	57·4 Te 39·5 Au 3·1 Ag same as Calaverite	58·63 Te 36·60 Au 3·82 Ag
B. Dark-coloured Ores—			
Petzite . . . . . (common)	$(Ag, Au)_2Te$ Ag : Au=3 : 1	32·8 Te 25·4 Au 41·8 Ag	31·5–34·8 Te 23·4–24·6 Au 40·4–43·3 Ag
Coloradoite	HgTe	61·51 Hg 38·49 Te	59·4–60·9 Hg 35·8–39·3 Te
C. Lead-grey Ores—			
Hessite . . . . (of little importance)	Ag_2Te	63·27 Ag 36·73 Te	...
Altaite . . . . . (of little importance)	PbTe	62·28 Pb 37·72 Te	...

Ores.[1]

Physical Properties.[2]	Chemical Reactions.[3]
Bronze-yellow. Yellowish-grey streak. Conchoidal fracture. Light metallic lustre. No cleavage. Sometimes resembles sulphur. Sp. Gr. = 9·0. H = 2·5. Cryst. Syst. = Asymmetrical.	(*a*) Upon charcoal in the oxidizing flame of the blowpipe gives a white incrustation, colours the flame bluish-green, and leaves a gold button. (*b*) In glass tube gives a black sublimate of tellurium, and a stable sublimate of telluric acid which when hot is yellow and when cold white. No gold button.
Silver-white. Cleavage perfect. Metallic lustre. Sp. Gr. = 7·9 – 8·3. H = 2·5. Cryst. Syst. = Monosymmetrical.	(*a*) Upon charcoal in the oxidizing flame gives a silver-gold button somewhat heavier than with calaverite. (*b*) In glass tube gives a sublimate of telluric acid.
Somewhat more yellow than sylvanite. Metallic lustre. Distinct cleavage. Sp. Gr. = above 8·35. Cryst. Syst. = Rhombic.	Decrepitates violently before the blowpipe, being in this distinguishable from sylvanite which it often resembles.
Steel-grey to iron-black. Metallic lustre. No cleavage. Conchoidal fracture. Sp. Gr. = 8·17 – 9·4. Cryst. Syst. = Cubic. In appearance greatly resembles coloradoite.	Upon charcoal in the oxidizing flame gives a small white incrustation and imparts a slight bluish-green colour to the flame. With sodium carbonate a white malleable button results which in nitric acid becomes a golden-yellow. Calaverite and sylvanite give a button without the necessity of adding sodium carbonate.
Iron-black. Conchoidal fracture. Metallic lustre. No cleavage. Black metallic streak. Sp. Gr. = 8·627. H = 2·5. Massive. So similar in appearance to petzite that chemical tests are generally needed to distinguish one from the other.	(*a*) Upon charcoal completely volatilizes with the formation of a white incrustation, the flame being coloured an intense bluish-green. (*b*) In glass tube fuses to a black button, gives a sublimate of mercury beads and a sublimate much less volatile of telluric acid which when hot is yellow and when cold is white. With a larger piece a black sublimate of tellurium is also obtained.
Lead-grey. Sp. Gr. = 8·07 – 8·56. H = 2·5 Cryst. Syst. = Cubic.	Similar to petzite, but white button completely soluble in nitric acid.
Lead-grey. Perfect cleavage in three directions at right angles. Cryst. Syst. = Cubic.	Lead and tellurium reactions.

[1] Krusch, 'Beitrag zur Kenntnis der nutzbaren Lagerstätten Westaustraliens,' *Zeit. f. prakt. Geol.*, 1903, p. 369.

[2] Hintze, *Lehrbuch der Mineralogie.*

[3] L. J. Spencer, 'Mineralogical Notes on Western Australian Tellurides,' *Mineralogical Magazine*, February 1903.

The telluride gold ores may be divided into two classes according to their colour, one being light and the other dark. Of the former the most important are sylvanite, calaverite, and krennerite, all of which have the general formula $AuTe_2$, the gold in each case being replaced to a varying extent by silver. Krennerite may contain as much as 39·5 per cent of gold, and sylvanite 24 per cent, while the silver may reach 11 per cent. These ores, which in their chemical composition are so nearly identical, may be distinguished by their cleavage. Sylvanite, known also as graphic tellurium, has a perfect cleavage in two directions in consequence of which it is easy to recognize; krennerite has an imperfect cleavage; and calaverite is without cleavage but has a conchoidal fracture. Among

FIG. 89.—Free gold (white) as specks in the lower half of the illustration, and as a filmy covering in the upper half; from the oxidation zone of a telluride lode. Great Boulder Perseverance, Kalgoorlie. Collection, *Geol. Landesanst.*, Berlin.

the dark telluride ores, the most common is petzite which has the formula $(Ag, Au)_2Te$. With this mineral also a large portion of the gold is generally replaced by silver. Nagyagite in addition to containing gold and tellurium, contains also lead, antimony, and sulphur. These two dark ores may be discriminated by the naked eye, petzite by its conchoidal fracture, and nagyagite by the ease with which it splits into flakes.

The comparatively easy differentiation of the light and dark telluride ores in the above manner, is complicated somewhat by the fact that petzite shows great resemblance to coloradoite, the mercury telluride, which occurs frequently in some deposits. Both are dark and both have conchoidal fracture, but a trained eye will recognize coloradoite by its bronze lustre. Also when heated on charcoal before the blowpipe coloradoite is entirely volatilized while petzite leaves a gold-silver button. In the statement on

pp. 80, 81, the most important characteristics by which the different telluride gold ores may be distinguished, have been assembled by Krusch from the works of Spencer, Hintze, and others.

The decomposition of telluride ores in the oxidation zone of deposits in which they occur, releases free gold in very characteristic form. It appears either earthy and of a brown colour, or in spongy aggregates of extremely small and well-formed crystals; or again either as film-like minutely crystalline coatings, as bright specks, or as flakes, this last condition being illustrated in Fig. 89. Free gold with such characteristics as these occurs only with the gold-telluride deposits. The brown colour which the country-rock assumes as the result of decomposition facilitates the recognition of the free gold simultaneously liberated.

The correct recognition of the oxidation zone of these deposits by the above-mentioned characteristics is also of great importance in making a valuation of any particular deposit. In Western Australia for instance it has been the experience that the oxidation zone of the gold-telluride lodes is poorer than the primary, possessing sometimes only one-half the gold content. As will be mentioned later when specially describing these occurrences, no cementation zone is found with them.

It is only within the last few years that gold-selenide ores have attracted attention. It has long been known that every telluride ore contained selenium more or less, but gold in association with selenium, occurring in such quantity as to constitute useful ore-deposits such as for instance those at Redjang Lebong and at Lebong Soelit in Sumatra, is a more recent experience. In consequence of the fineness in which this ore is distributed in the quartzose gangue at the two mines mentioned, it has not yet been found possible to determine exactly and in a manner free from objection, the nature of this association.

2. *Platinum- and Osmium Ores.*

Native platinum is only known in the unaltered condition, though it nearly always contains iridium, rhodium, osmium, and ruthenium, with some iron. Its atomic weight ranges between 14 and 19 and its percentage content varies accordingly. All that which has hitherto been won has been obtained from gravel-deposits. It is known also to occur in the primary condition, though in unprofitable amount, in magmatic segregations of basic eruptive rocks. Since the application of metallic osmium in the manufacture of electric lamps native platinum in addition to native osmium and osmo-iridium, has been regarded as an osmium ore.

The arsenide of platinum, sperrylite, $PtAs_2$, occurs only as a mineralogical curiosity. The small but constant amount of platinum always

present in nickeliferous pyrrhotite is mentioned more particularly when describing those deposits.

3. *Quicksilver Ores.*

Ores.	Chemical Composition.	Percentage Content.
Cinnabar, stahlerz, lebererz, korallenerz, idrialite, meta-cinnabarite	HgS, sometimes with more or less bitumen	86·2 in pure cinnabar
Quicksilver-tetrahedrite . .	$4[(Ag, Cu \text{ or } Hg)_2S(Sb \text{ or } As)_2S_3] + 4[(Fe, Zn)S(Sb \text{ or } As)_2S_3]$	Undetermined
Quicksilver	Hg	...

The principal ore though it may not always be primary is quicksilver, which mineral, as illustrated in Figs. 90 and 91, usually occurs in cracks

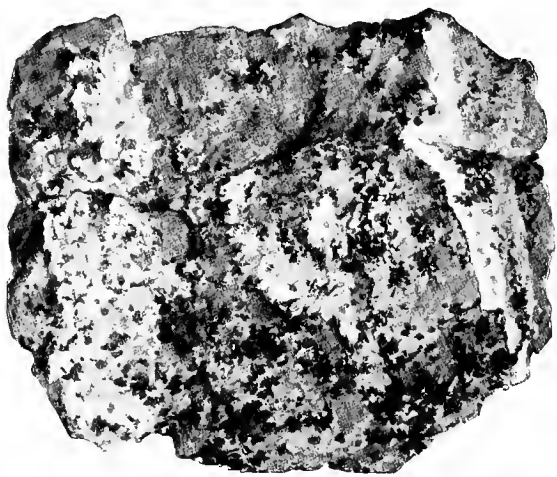

FIG. 90.—Spots of cinnabar in Carboniferous sandstone, the result of both pore-filling and metasomatic replacement. Nikitovka. Ekaterinoslav. Collection, *Geol. Landesanst.*, Berlin.

and rock pores. Hepatic quicksilver, idrialite, etc., which are admixtures of cinnabar and bitumen, are likewise primary; quicksilver tile-ore is similarly a mixture of cinnabar and dolomite. Quicksilver-tetrahedrite appears chiefly as an important cementation ore above sulphide deposits, though it may also occur to a small extent as a primary ore. Cinnabar itself, occurs secondary near the surface of such deposits as carry quicksilver-tetrahedrite in greater depth. Native quicksilver appears chiefly as an oxidation ore at the outcrops of deposits of cinnabar and quicksilver-tetrahedrite, or immediately at or in the neighbourhood of disturbances affecting such deposits; with other metals it forms amalgam. Meta-

cinnabarite, which is the black modification of cinnabar, occurs too rarely to allow any general statement to be made concerning it.

It is of importance to bear in mind that the occurrence of cinnabar

Fig. 91.—Cinnabar (dark) filling cracks in Triassic limestone. Becchi near Taragona, Spain. Collection, *Geol. Landesanst.*, Berlin.

in the oxidation zone is not sufficient in itself to demonstrate a primary deposit, since in greater depth quicksilver-tetrahedrite or some other and rarer ore of mercury may occur. The occurrence of native quicksilver at the surface is attended with the same possibility.

4. *Silver Ores.*

Ores.	Chemical Composition.	Percentage Content.
Argentiferous galena, sphalerite, pyrite, chalcocite, chalcopyrite	...	Variable
Native silver	Ag	72–99·9
Argentite	Ag_2S	87·1
Diskrasite	Ag_2Sb ?	64·3–94·1
Arsen-silver	Ag_3As ?	...
Polybasite	$(AgCu)_9SbS_6$	64–72, Cu 3–10
Stephanite	Ag_5SbS_4	68·4
Argentiferous tetrahedrite	$4(Cu_2Ag_2FeZn)S . Sb_2S_3$	to 32, Cu to 38
Stromeyerite	$(CuAg)_2S$	33·1, Cu 31·1
Pyrargyrite	Ag_3SbS_3	60·0
Proustite	Ag_3AsS_3	65·4
Cerargyrite	AgCl	75·2
Bromargyrite	AgBr	57·4
Iodyrite	AgI	to 45·9

In this statement those ores characteristic of the primary and the cementation zones are given first, while those of the oxidation zone are placed at the bottom. It is however important to remember that some of the first may occur both in the primary as well as in the cementation zone.

The most frequent primary ores are argentiferous galena, sphalerite, and pyrite ; native silver is primary to a smaller extent, and still less often

do the other sulphides, antimonides and arsenides, occur in the primary zone. The cementation ores are native silver, argentite, diskrasite, arsensilver, stephanite, argentiferous tetrahedrite, pyrargyrite and proustite. The large occurrences of the two last ores for instance are found in greatest part within this zone. The ores of the oxidation zone are cerargyrite, which occurs very frequently and, though in smaller amount, native silver. Bromargyrite and iodyrite are rare and postulate certain special influences acting upon the primary ore, a subject more fully discussed in the chapter dealing with the formation of minerals.

FIG. 92.—Secondary silver (bright) upon the cleavage-planes of galena from the cementation zone.

Argentiferous galena, from which practically two-thirds of the entire silver production is obtained, occurs both as primary and as cementation ore. While in the first condition the silver is regularly distributed and assays as high as 500 grm. per ton are rarely obtained, in the galena of the cementation zone native silver occurs in addition filling, as illustrated in Figs. 92 and 139, all the cracks and crevices so that assays of 10 kg. and more are reached.

In view of the great difference of metal content between the different zones, the correct recognition of the indicator ores is of the greatest importance.

5. *Lead Ores.*

Ores.	Chemical Composition.	Percentage Content.
Galena . . .	PbS	86·6, Ag 0·03–0·1 generally
Boulangerite .	$Pb_5Sb_4S_{11}$	55·4
Bournonite . .	$(Pb, Cu_2)_3Sb_2S_6$	42·6, Cu 14
Jamesonite . .	Pb_2Sb_2S5	50·8
Cerussite . .	$PbCO_3$	73·0
Anglesite . .	$PbSO_4$	68·3
Phosgenite . .	$PbCl_2PbCO_3$	74·2
Pyromorphite .	$Pb_5Cl(PO_4)_3$	75·8
Mimetite . .	$Pb_5Cl(AsO_4)_3$	69·6

In this list also the ores are arranged from primary ores at the top to oxidation ores at the bottom. The oxidation ores include pyromorphite, mimetite, phosgenite, anglesite, and cerussite. Jamesonite, boulangerite, and bournonite, are to be considered as cementation ores though in one and the same occurrence they may also be found in the primary zone. Similarly though the typical ore of the primary zone is argentiferous galena that ore, as mentioned under silver ores, may also occur in the cementation zone.

If the lead content only be considered, then experience in lead deposits does not allow it to be said that any material migration of the metal content has taken place. The ores in the oxidation zone have still a high content while those of the cementation zone are actually poorer than those that are primary. The recognition of the ores characteristic of the different zones is therefore important rather on account of the noble metals present than because of the lead.

6. *Zinc Ores.*

Ores.	Chemical Composition.	Percentage Content.
Sphalerite	(Zn, Fe, Mn, Cd)S	50–67
Franklinite	$(ZnMn)Fe_2O_4$	13·6–20
Zincite	ZnO	72–80
Willemite	Zn_2SiO_4	58·5
Hemimorphite	$H_2Zn_2SiO_5$	54·2
Calamine	$(Zn\cancel{CO_3}OH)_2SiO_3$	~~52·0~~ 52.0
Hydrozincite	$ZnCO_3 . 2Zn(OH)_2$	60·0

With zinc ores a differentiation according to genesis is first necessary. While sphalerite appears in deposits of whatever genesis, franklinite, zincite, and willemite, are practically limited to the contact-deposits, one occurrence being illustrated in Fig. 93, leaving hemimorphite, calamine, and hydrozincite, to occur to a large extent in metasomatic deposits.

The closer study of the metasomatic zinc deposits shows that the ores of these are in greater part secondary, as illustrated in Fig. 94, and that they represent, as it were, the oxidation zone of deposits often unprofitable in their primary sulphide condition. They may accordingly be regarded as oxidation ores, though it must be remarked that in such metasomatic deposits the limestone undergoing alteration passes directly over to the carbonate or the silicate of zinc. A secondary character to the ores named harmonizes moreover with the fact that they are also characteristic of the oxidation zone of the sulphide zinc lodes.

Zinc ores may therefore be divided into oxidation and primary ores.

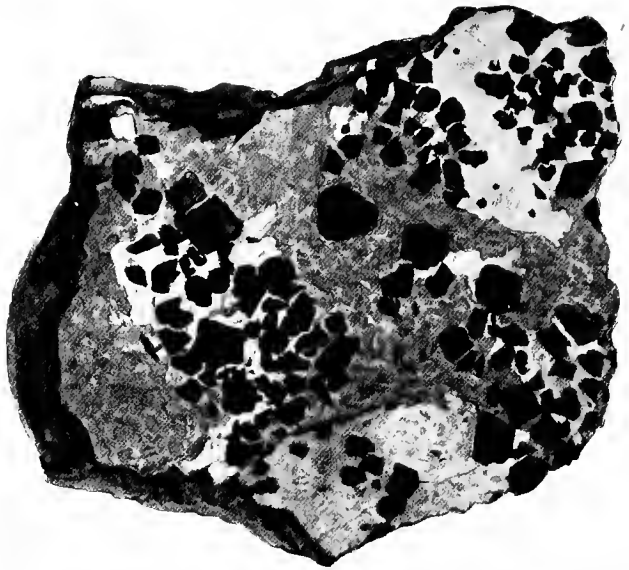

FIG. 93.—Primary zincite (black) in the contact-metamorphic limestone of Franklin Furnace, New Jersey. Collection, *Geol. Landesanst.*, Berlin.

FIG. 94.—Metasomatically formed schalenblende (white with grey stripes) altered, except for some fragments, to smithsonite. Oxidation zone of the Schmalgraf mine near Aachen. Collection, *Geol. Landesanst.*, Berlin.

Typical ores such as would constitute a cementation zone have not yet been observed.

7. *Copper Ores.*

Ores.	Chemical Composition.	Percentage Content.
Cupriferous pyrite and pyrrhotite	Variable	Variable
Chalcopyrite	$CuFeS_2$	34·5
Native copper	Cu	to 100·0
Chalcocite	Cu_2S	79·8
Tetrahedrite	$4Cu_2S \cdot Sb_2S_3$	30–55
Bornite	Cu_3FeS_3	55·5
Atacamite	$CuCl_2 \cdot 3Cu(OH)_2$	59·4
Azurite	$2CuCO_3Cu(OH)_2$	55·2
Malachite	$CuCO_3Cu(OH)_2$	57·4
Chrysocolla	$H_2CuSiO_4H_2O$	22·4–36·0
Cuprite	Cu_2O	88·8
Melaconite	Earthy oxide	Variable
Covellite	CuS	66·4

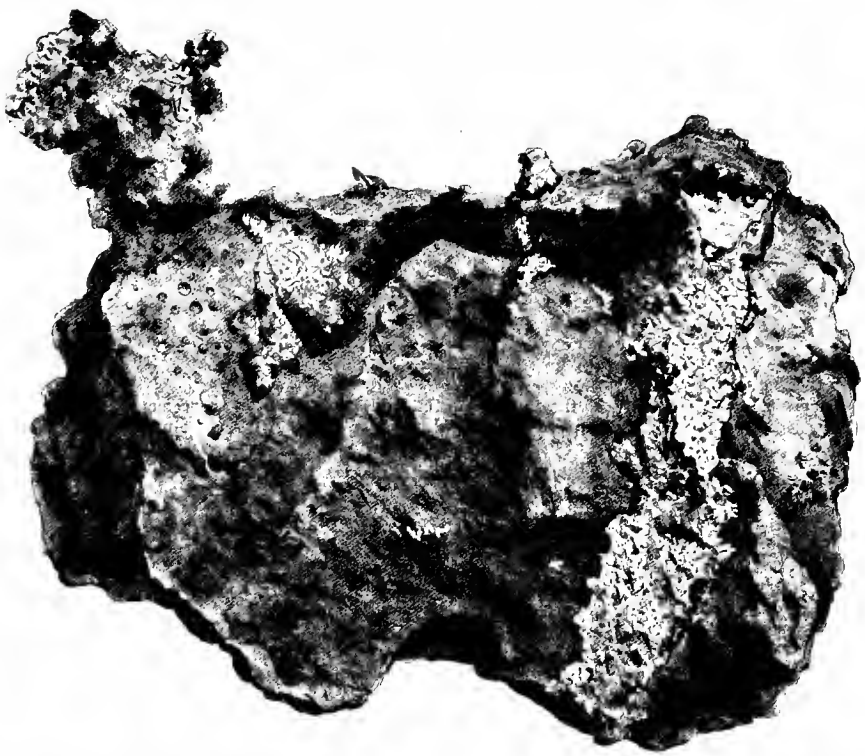

FIG. 95.—Primary native copper (white and light grey) in veins and vesicules in melaphyre, with epidote and calcite. Lake Superior. Franklin mine, Houghton Co., Michigan. Collection, *Geol. Landesanst.*, Berlin.

Cupriferous pyrite, a mechanical mixture of pyrite and chalcopyrite, is the ore most widely distributed. After this come cupriferous pyrrhotite and chalcopyrite; and then, though more unusual, native copper as illustrated in Fig. 95. Malachite, azurite, atacamite, chrysocolla, cuprite illustrated in Fig. 96, and melaconite, all belong to the oxidation zone in which also covellite and, as illustrated in Fig. 97, native copper may occur, though much more seldom. These ores generally occur as impregnations and fracture linings, so that the copper content as a rule is small, reaching at

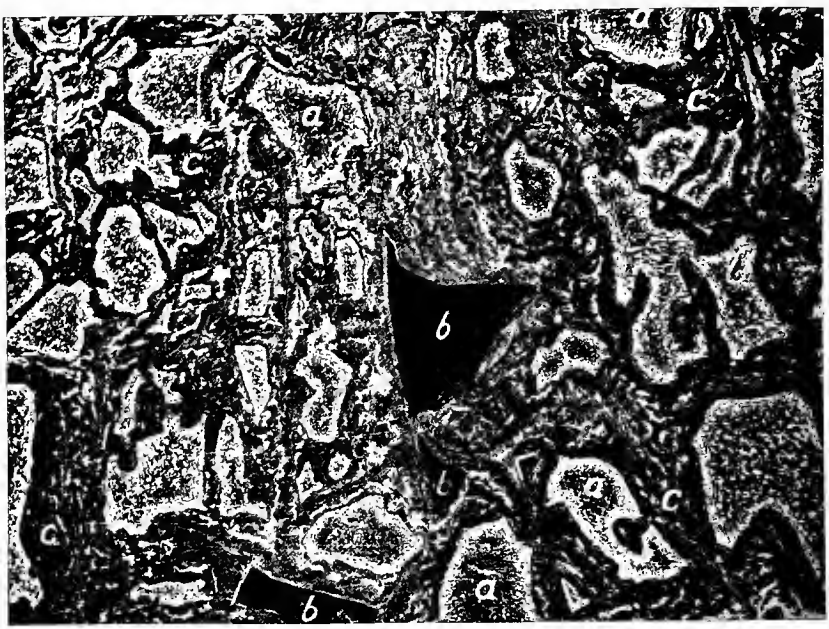

FIG. 96.—Chalcopyrite, at the junction of the oxidation zone with the cementation zone, in process of decomposition to cuprite and malachite. Bolivar, Santander, Columbia. Magnified 18 times.

(*a*), Kernels of chalcopyrite, decomposed around outlines; (*b*), malachite; (*c*), cuprite.

most only a low percentage. The typical cementation ores are chalcocite, chalcopyrite, bornite, and native copper. These at times occur in large quantities, a fact particularly distinctive of the cementation zone of copper deposits, which zone is illustrated in Figs. 98 and 99. The three first named of the cementation ores often, and native copper exceptionally, occur as primary ores. The position occupied by tetrahedrite has not yet been definitely settled, experience so far would indicate that it occurs more particularly in the cementation zone.

In consequence of the ease with which copper ores go into solution, the decomposition of the primary ores and the resulting migration of the metal

content are as with gold ores factors of considerable moment, especially as the differences in the metal content of the different zones are equally

FIG. 97.—Native copper along cracks in quartz ; from the oxidation zone, Ocaruzawa, Rikuchu, Japan. Collection, *Geol. Landesanst.*, Berlin.

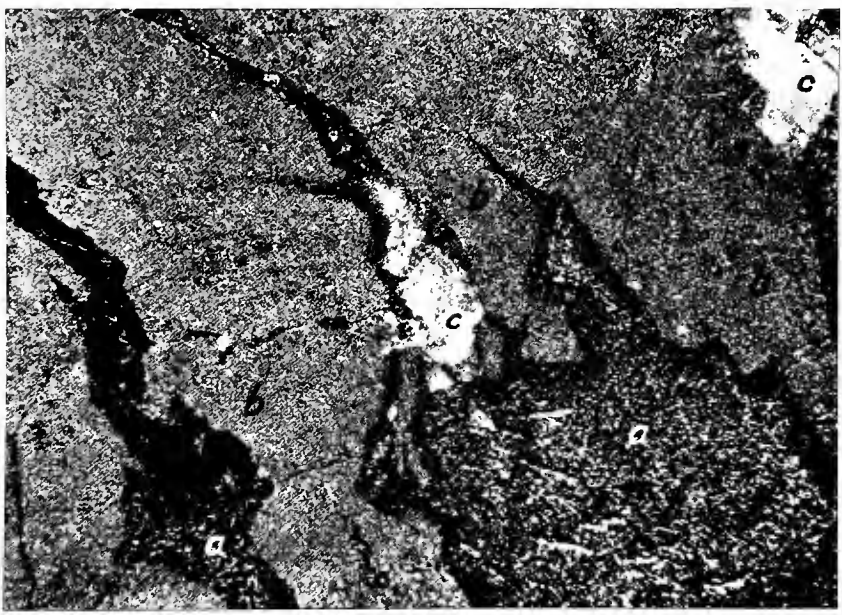

FIG. 98.—Chalcopyrite, showing marginal decomposition, cemented throughout pyrite ; from the cementation zone, Rio Tinto. Magnified 18 times.

(*a*), Chalcopyrite ; (*b*), pyrite ; (*c*), calcite.

strongly marked. The proper appreciation of the ores characteristic of each zone is often therefore of the greatest importance when making a

valuation of a copper deposit. The question as to how deep a deposit of rich copper ore may be expected to extend depends a good deal upon observation of these indicator ores for an answer.

8. *Iron Ores.*

Ores.	Chemical Composition.	Percentage Content.
Magnetite	Fe_3O_4	72·41
Hæmatite } Specularite }	Fe_2O_3	70·00
Limonite	$2Fe_2O_3 . 2H_2O$ to $Fe_2O_3 . H_2O$	to 60
Siderite	$FeCO_3$	48·3
Chamoisite	Hydrous ferrous aluminium silicate	28–37
Thuringite	Hydrous ferric aluminium silicate	32–40
Clay Ironstone	Hæmatite and siderite with clay	...
Blackband Ironstone	Siderite with clay and carbon	...

Iron ores, as is to be seen from this table, may be divided into oxidized, carbonaceous, and siliceous ores. The most important of them all is magnetite which, as produced, generally contains 70 per cent of iron. Afterwards follow hæmatite, limonite, siderite, and the silicates.

FIG. 99.—Bornite, metasomatically replacing chalcopyrite represented by the light core in the centre. Monte Catini, Val di Cecina, Tuscany. Collection, *Geol. Landesanst.*, Berlin.

The oxides and hydrates being very stable are little prone to alteration. Although pseudomorphs of specularite after magnetite and magnetite after specularite are known, and also the alteration of limonite to hæmatite and the reverse, such secondary action brings with it no important change in the

iron content. When oxidized ores therefore are found in workings near the surface the possibility exists that they will also be found in the primary zone. With siderite the case is different. This mineral in general is limited to the primary zone since, as illustrated in Figs. 100 and 101, it tends at the surface to form limonite or less often hæmatite. Deposits of this ore are in consequence at the surface generally represented by limonite, the red colour of the gossan in such cases being due not to hæmatite but to the red hydrate. It follows therefore that limonite occurring near the surface may be but the oxidation product of siderite existing in depth. As the difference in iron content between these two is

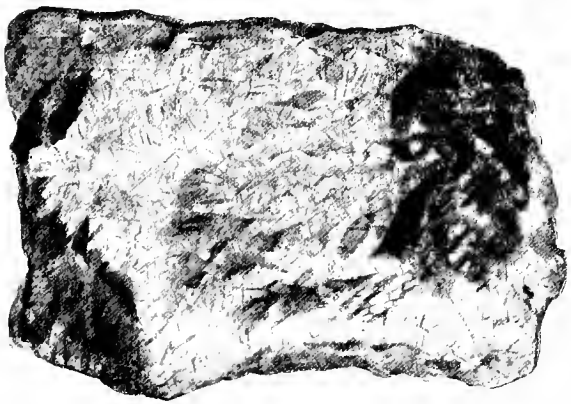

FIG. 100.—Siderite (light) passing over to hæmatite (dark). Storch and Schöneberg mine, near Siegen. Collection, *Geol. Landesanst.*, Berlin.

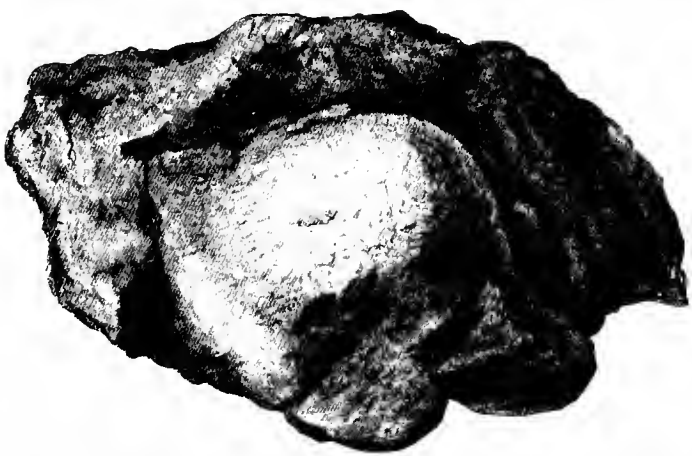

FIG. 101.—Limonite, represented by the dark border, formed from siderite, represented by the light core; from the oxidation zone, Kamsdorf. Collection, *Geol. Landesanst.*, Berlin.

considerable, there is a possibility that the content of the primary deposit will be over-estimated if the limonite found at the surface be not recognized as an oxidation product. The most general indications of secondary character are a porous and drusy structure and the occurrence

of stalactites, these being due to the fact that the hydrate occupies a smaller space than the carbonate. The occurrence of limonite as a decomposition product of pyrite is discussed on p. 104.

Chamoisite and thuringite are also primary ores. They are seen at the surface only in peculiarly favourable circumstances since, as

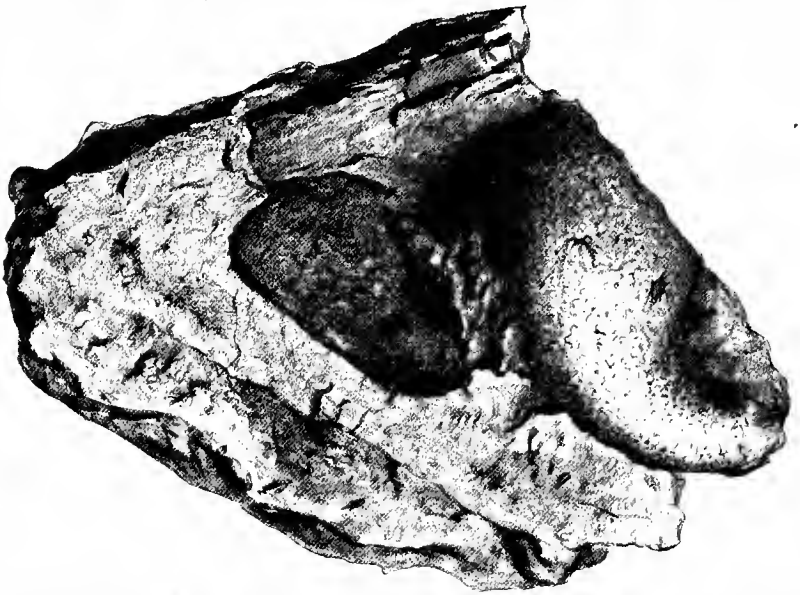

FIG. 102.—Chamoisite, represented by the dark round core, passing over to limonite around its borders; from the oxidation zone, Nuovic in Bohemia. Collection, *Geol. Landesanst.*, Berlin.

illustrated in Fig. 102, they pass readily to hæmatite and limonite. This tendency on their part makes it possible that with them also the primary ore beneath may be over-estimated, though as they generally occur in beds and the resulting oxides often retain the oolitic and earthy structure characteristic of these ores, there is usually sufficient evidence that the primary ore is neither hæmatite nor limonite.

9. *Manganese Ores.*

Ores.	Chemical Composition.	Percentage Content.
Psilomelane	MnO_2 with MnO, BaO or K_2O	49–62
Polianite	MnO_2	63·2
Pyrolusite	MnO_2	to 63
Manganite	Mn_2O_3, H_2O	62·5
Braunite	(Mn, Ba)(Mn, Si)O_3	to 69·6
Hausmannite	Mn_3O_4	72·0
Rhodonite	$MnSiO_3$	41·9
Rhodochrosite	$MnCO_3$	47·2
Wad	MnO_2, nMnO with 10–15% H_2O	Variable

It is seen that manganese ores may be divided into two groups; oxides and hydrated oxides; carbonates and silicates. Of the first, psilomelane, polianite, and pyrolusite, are the most frequent while manganite, hausmannite, and wad, occur more sparingly. The ores of the second group have naturally a materially lower metal content than the oxides.

With the possible exception of wad all the ores named may occur in the primary zone. While however rhodonite and rhodochrosite are limited to that zone, the other ores may also, as the products of these two exclusively primary ores, occur in the oxidation zone. When oxides or hydrated oxides constitute the primary deposit, no characteristic ores are formed in the zone of oxidation, because of the stability of the primary ores in those cases. Deposits therefore exhibiting these ores near the surface may prove also to contain them in depth; the possibility is however present, especially when the ore is drusy, that in depth they may pass to the carbonate or the silicate.

10. *Nickel Ores.*

Ores.	Chemical Composition.	Percentage Content.
Nickeliferous pyrrhotite and pyrite	...	to 5·0 and more
Garnierite	Hydrous nickel-magnesium silicate	to 20·0
Pimelite	,,	Variable
Schuchardite	,,	,,
Chloanthite	$NiAs_2$	28·1
Gersdorffite	NiAsS	35·4
Niccolite	NiAs	43·9
Annabergite	$Ni_3As_2O_8 . 8H_2O$	...

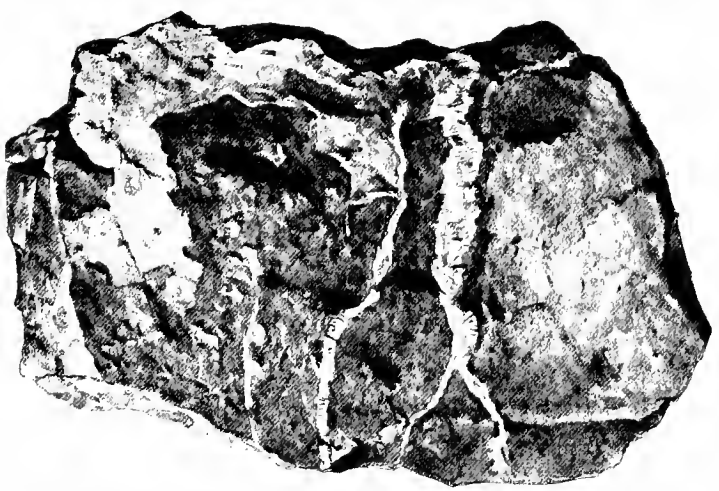

Fig. 103.—Pimelite veins formed by lateral secretion in decomposed serpentine. Frankenstein in Silesia. Collection, *Geol. Landesanst.*, Berlin.

The differentiation of nickel ores according to their genesis is more important than that according to their horizon in any deposit. Garnierite, pimelite, and schuchardite, are hydrous silicates of magnesium with very varying nickel content; their occurrence, illustrated in Fig. 103, is limited to veins in serpentine. Chloanthite, gersdorffite, and niccolite, occur only in normal fissures similar to the lead-silver-zinc lodes, one such nickel occurrence being illustrated in Fig. 104. Deposits of nickeliferous pyrrhotite and pyrite—the nickel content of both being due almost entirely to a mechanical and extremely fine admixture of pentlandite the sulphide of nickel and iron—occur only as magmatic segregations in basic eruptive rocks. The occurrence of such nickel pyrrhotite is illustrated in Fig. 105.

FIG. 104.—Smaltite vein (dark) containing niccolite (dark grey) and smaltite (light grey), and itself contained in dolomite and calcite. Hydrochemical filling. Cobalt, Canada. Collection, *Geol. Landesanst.*, Berlin.

Concerning relation to the oxidation and cementation zones the following may be said. Annabergite, the hydrous arsenate, occurs only

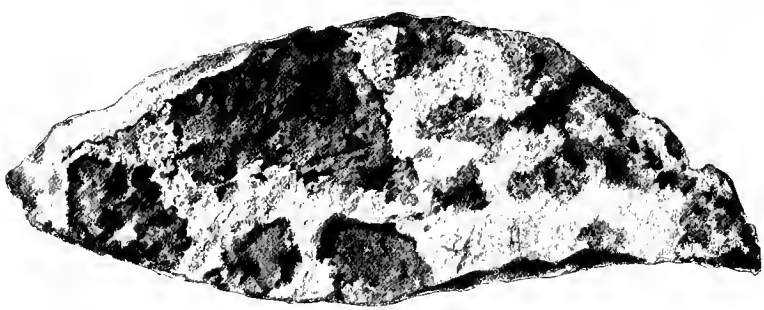

FIG. 105.—Nickel-pyrrhotite (dark grey to black) and chalcopyrite (light grey) magmatically separated in amphibolite. Gertrude mine, Sudbury, Canada. Collection, *Geol. Landesanst.*, Berlin.

as a filmy coating, the product of the oxidation of arsenide and sulphide ores. Where an oxidation zone exists with a deposit containing such

ores, a mixture of iron oxide, manganese oxide, and the oxides of nickel and cobalt, is usually found, though as such mixtures are comparatively rare it is probable that they require some special circumstances, say large quantities of water, for their formation. While among the hydrated compounds containing nickel and magnesium no ores are known to be limited to any particular zone, it is nevertheless the case that under the deposit of garnierite at Malaga a magmatic deposit of niccolite was found, a specimen from which is illustrated in Fig. 106. At Frankenstein in Lower Silesia also, it was recently held that a mixture of sulphide ores might, as the result of their decomposition by thermal action, be the source of the silicated nickel ore found there. This has however not been confirmed by later observation, and to state that the hydrous nickel silicates in general were the oxidized or decomposition products of nickel arsenides, would therefore be going too far.

FIG. 106. — Niccolite (light) magmatically separated in a mixture of plagioclase and augite. Los Jarales near Caratraca, Malaga. Collection, *Geol. Landesanst.*, Berlin.

11. *Cobalt Ores.*

Ores.	Chemical Composition.	Percentage Content.
Cobalt-arsenopyrite	(FeCo)AsS	6–25
Cobaltite	CoAsS	35·4
Linnæite	$(CoNi)_3S_4$	Variable
Skutterudite	$CoAs_3$	20·7
Smaltite	$CoAs_2$	28·2
Cobaltiferous pyrrhotite and pyrite	...	Low
Asbolane	Cobaltiferous decomposition product	Variable
Erythrite	$Co_3As_2O_8 . 8H_2O$	...

As may be seen from this table the ores of cobalt like those of nickel may according to their genesis be separated into three sharply defined groups: first, the arsenide-sulphide ores such as cobalt-arsenopyrite, cobaltite, linnæite, skutterudite, and smaltite, which occur in normal veins and also, as illustrated in Fig. 107, in impregnated beds of crystalline schist; second, the oxidized ores, such as asbolane, which, as illustrated in Fig. 108, occur in veins in serpentine; and third, cobaltiferous pyrrhotite and pyrite, which have their origin in magmatic differentiation.

In relation to surface decomposition cobalt ores stand in much the same position as those of nickel. Erythrite occurs entirely as a filmy covering

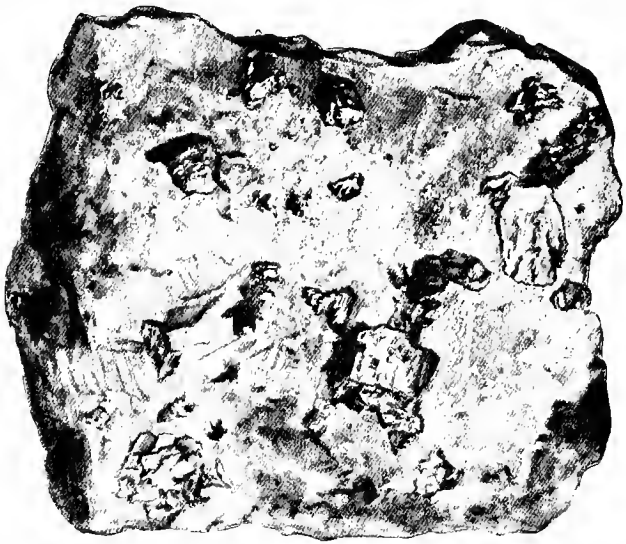

FIG. 107.—Primary cobaltite crystals in crystalline schist from the Skutterud mine near Modum. Collection, *Geol. Landesanst.*, Berlin.

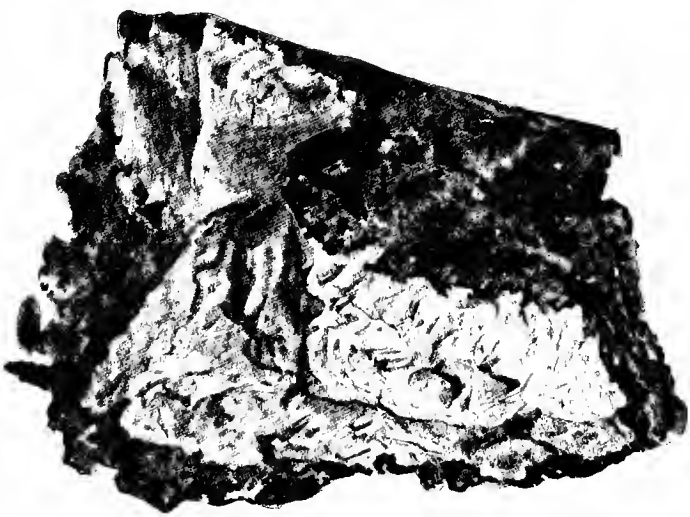

FIG. 108.—Asbolane (black and dark grey) in decomposed serpentine (white and light grey). Portion of an asbolane vein from New Caledonia. Collection, *Geol. Landesanst.*, Berlin.

over the arsenide-sulphide ores, of which ores the typical decomposition product in the oxidation zone is a fine powdery mixture of iron and cobalt

oxides. This mixture occurs however comparatively seldom, probably because its formation appears to depend upon the action of large quantities of water.

12. *Chromium Ores.*

Practically the only ore of chromium is chrome-iron or chromite, which has the composition $(Fe, Mg)(Cr_2, Al_2, Fe_2)O_4$ and usually contains from

FIG. 109.—Chromite (dark) with specks of niccolite (white spots) in serpentine at Santa de Aguas, Malaga. Collection, *Geol. Landesanst.*, Berlin.

35·5 to 40 per cent of chromium. This ore is characterized by its great resistance to atmospheric decomposition in consequence of which it is particularly prone to occur in gravel-deposits.

13. *Tin Ores.*

Ores.	Chemical Composition.	Percentage Content.
Cassiterite, including wood-tin .	SnO_2	78·6
Stannite	Cu_2FeSnS_4	27·6
Stanniferous pyrite . . .	...	...

With the exception of wood-tin these ores are all primary, though while cassiterite because of its great stability neither forms any secondary minerals nor allows any subsequent migration of its metal content, stannite and stanniferous pyrite on the other hand appear to undergo changes similar to that of cupriferous pyrite, from which changes it is considered that wood-tin results. Wood-tin therefore represents the case of secondary tin enrichment.

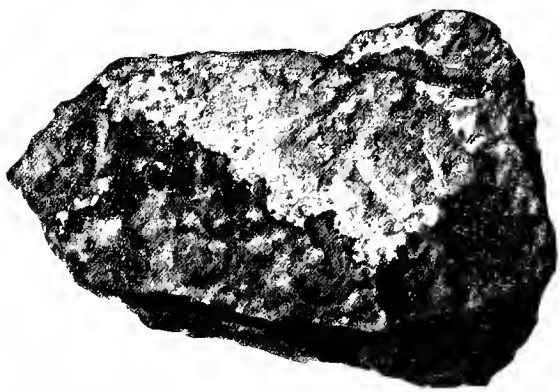

FIG. 110.—Cassiterite (dark) and stanniferous pyrite (light). Primary ore from the Bolivian lodes. Avicaya, North Bolivia. Collection, *Geol. Landesanst.*, Berlin.

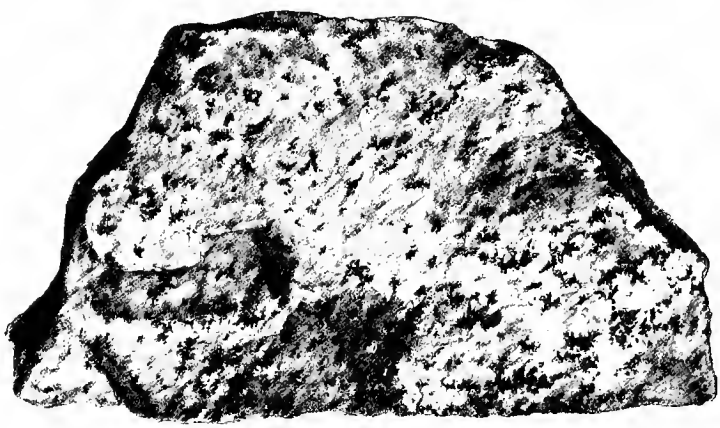

FIG. 111.—Cassiterite (dark) disseminated in greisen ; primary ore from Geyersberg near Geyer. Collection, *Geol. Landesanst.*, Berlin.

14. *Bismuth Ores.*

Ores.	Chemical Composition.	Percentage Content.
Bismuthinite . . .	Bi_2S_3	81·2
Native bismuth . . .	Bi	95–99·9
Bismite	Bi_2O_3	89·6
Bismuthite	$Bi_2CO_5 . nH_2O$	80–82

Although up to the present but little has been observed concerning secondary variation in the deposits of these ores, the manner in which they make their appearance indicates that there are primary ores which

can be distinguished from those more likely to be secondary. Among these comparatively uncommon ores bismuthinite is the most frequent, and without doubt it is in most cases primary. Bismite and bismuthite on the other hand are oxidation ores occurring in greater part as thin filmy coverings deposited upon other minerals.

15. *Antimony Ores.*

Ores.	Chemical Composition.	Percentage Content.
Stibnite	Sb_2S_3	71·4
Cervantite	SbO_2	79·0
Stiblite	$2SbO_2 . H_2O$	74·5
Valentinite, Senarmontite .	Sb_2O_3	83·2

In the case of these ores also, but few observations have been possible. The most common primary antimony ore is stibnite, of which stiblite and valentinite are the oxidized products. Cementation antimony ores are not known although stibnite, similarly to galena, reacts on solutions of the noble metals; for instance it precipitates gold in bright scales from a solution of gold chloride. Although therefore no cementation ore may be defined in reference to the antimony content, this is well possible in relation to the content of the noble metals. In such a case the stibnite would behave as galena does among the silver ores.

16. *Arsenic Ores.*

Ores.	Chemical Composition.	Percentage Content.
Löllingite	$FeAs_2$	72·8
Arsenopyrite	FeAsS	46·0
Orpiment	As_2S_3	60·9
Realgar	As_2S_2	70·1
Native arsenic	As	90–100
Arsenolite	As_2O_3	...

The five ores first named in this table occur as primary ores, though they differ among themselves in the manner of their genesis. While arsenopyrite, löllingite, and native arsenic, occur chiefly in lodes, the larger masses of orpiment and realgar appear to be confined to contact-deposits. Arsenolite, the one typical oxidation ore, is only of subordinate importance. On the other hand it is established that arsenopyrite occurs in auriferous deposits as a cementation ore with high gold content. Native arsenic occurs similarly in argentiferous deposits, exhibiting itself in such circumstance either in botryoidal form or in large finely-granular masses.

17. *Wolfram Ores.*

Ores.	Chemical Composition.	Percentage Content.
Wolframite . . .	$mFeWO_4+nMnWO_4$	to 75 WO_3
Scheelite	$CaWO_4$	to 80 WO_3

These two equally important wolfram ores, since the more extended employment of wolfram steel, have been the object of considerable attention. From the above formula it is seen that in wolframite the relation of the iron to the manganese varies, a fact which also appears to make itself evident in the varying colour of the ore ; when rich in manganese it appears black, and when containing much iron it is distinguished by being brown. Leaving out of consideration the very rare mineral stolzite, $PbWO_4$, no oxidation or cementation ores are known. From signs of decomposition which have been observed with wolframite, which signs consist in the formation of a brown crust apparently of ferric hydrate, it would appear however that this mineral is not entirely proof against the decomposing forces of the atmosphere and that consequently it is possible an oxidation ore may exist.

18. *Molybdenum Ores.*

The only molybdenum ore is molybdenite, MoS_2, with 60 per cent of molybdenum.

19. *Uranium Ores.*

Ores.	Chemical Composition.	Percentage Content.
Pitchblende	$(UPb)_2 . 3U_2O_{12}$	80–85$(UO_2)O$
Uranium-ochre	Uncertain	Variable
Copper-uranite	$CuO . 2(UO_2)O . P_2O_5 . 8H_2O$	61$(UO_2)O$
Calcium-uranite	$CaO . 2(UO_2)O . P_2O_5 . 8H_2O$	63$(UO_2)O$

In addition to those mentioned there are other and rarer ores of this uncommon metal. As these ores constitute the raw material from which radium is produced they have all enjoyed a much greater importance since the discovery of that element. In consequence however of their rarity and of the irregularity of their occurrence, very few observations relative to secondary alteration have been possible.

20. *Thorium- and Cerium Ores.*

Ores.	Chemical Composition.	Percentage Content.
Monazite	(Ce, La, Di)PO_4 with Th	to 18·0% ThO_2 and 31·3 CeO
Thorite	$ThSiO_4$ but generally with water	81·5 ThO_2

These two minerals, which perhaps can hardly be classed as ores in the usual sense of the term since their treatment rests with the chemical industry, differ in their genesis. Monazite occurs in minute quantities as an accessory constituent of granite and also in dykes within that rock, this latter occurrence having been noted in South Africa. The useful deposits of this ore are however without exception marine or fluviatile gravels.

Thorite, which occurs generally as minute grains in dykes of pegmatite-granite or syenite but also as a curiosity in the apatite lodes of Norway, is now no longer worked for the production of thorium. The orange-coloured variety known as orangite and the dark-brown or black variety, being weathered and hydrated, do not agree exactly with the theoretical formula; the latter supposedly represents a more advanced stage in this weathering than orangite.

With regard to cerium, there are no important ores worked exclusively for that metal because the greater number of the thorium ores contain cerium at the same time and in the production of thorium nitrate this also is recovered.

21. *Aluminium Ores.*

Ores.	Chemical Composition.	Percentage Content.
Bauxite	$Al_2O_3 . 2H_2O$	50–70
Diasporite . . .	$Al_2O_3 . H_2O$	50–70
Cryolite	Na_3AlF_6	12·85

As mentioned when discussing the definition of ore, those compounds from which aluminium on a large scale is obtained must, according to German usage, be regarded as aluminium ores. Those mentioned above differ greatly in origin; bauxite and diasporite are usually alterations of limestone in contact-zones and also to some small extent decomposition products of different basic eruptive rocks, especially basalt; whereas cryolite occurs in lodes in granite. The name diasporite used here for the first

time is proposed for a contact alteration product which, as indicated by microscopical investigation, consists almost entirely of the mineral diaspore and which contains only half as much water as bauxite. The ores mentioned are primary and no secondary ores are known.

22. *Sulphur Ores.*

Ores.	Chemical Composition.	Percentage Content.
Pyrite	FeS_2	53·4
Marcasite	FeS_2	53·4
Pyrrhotite . . .	FeS	38·4–40
Chalcopyrite . . .	$CuFeS_2$	34·9
Native sulphur . .	S	to 100

It has already been pointed out that although in recent years the residues after the roasting of pyrite have been used as iron ore, with sulphur ores it is the sulphur content and not that of the combined metal which is of importance. The sulphur ores may be divided into two groups, they are either sulphides such as pyrite, or they are impregnations of native sulphur in rock. All are primary, though chalcopyrite sometimes is also secondary. By decomposition the pyrite loses sulphur until at last, even though a good deal of copper may have been present originally, a poor iron ore results, practically free from copper. That this iron ore has actually resulted from pyrite may be gathered from the corroded appearance of the country-rock, such corrosion doubtless being due to the sulphuric acid formed at the decomposition of the pyrite.

II. Gangue, Matrix, and Lodestuff

Those minerals which occur beside the ore in deposits are in England included under the term ‘gangue.’ More particularly those which occur in lodes form the ‘lodestuff’ and those in any other deposit the ‘matrix.’ The most common gangue minerals are quartz and chalcedony. While formerly the white finely-crystalline masses of silica occurring in lodes were without question taken to be quartz, microscopic investigation—which, indebted not a little to the researches of Beck and Vogt, is entering ever deeper into the study of ore-deposits—shows that a considerable portion of the silica in these lodes is in the form of chalcedony or of a mixture of quartz and chalcedony. This is especially the case, as illustrated in Fig. 112, with banded masses of silica. Opal occurs less often in this connection. With large lodes there often appears to be a regular arrangement of the chalcedony near the walls and the quartz in the centre. If such lodes be

considered as referable to the activity of hot mineral springs, this regular arrangement agrees with the results of investigation in the laboratory, according to which quartz separates from solutions at a higher temperature than chalcedony. Since the country-rock can but have a cooling effect upon the solutions the condition of lower temperature favourable to the deposition of chalcedony appears to be fulfilled near the walls.

The appearance of the quartz in ore-deposits is not always the same. Sometimes it is milky white, sometimes colourless; its lustre may be

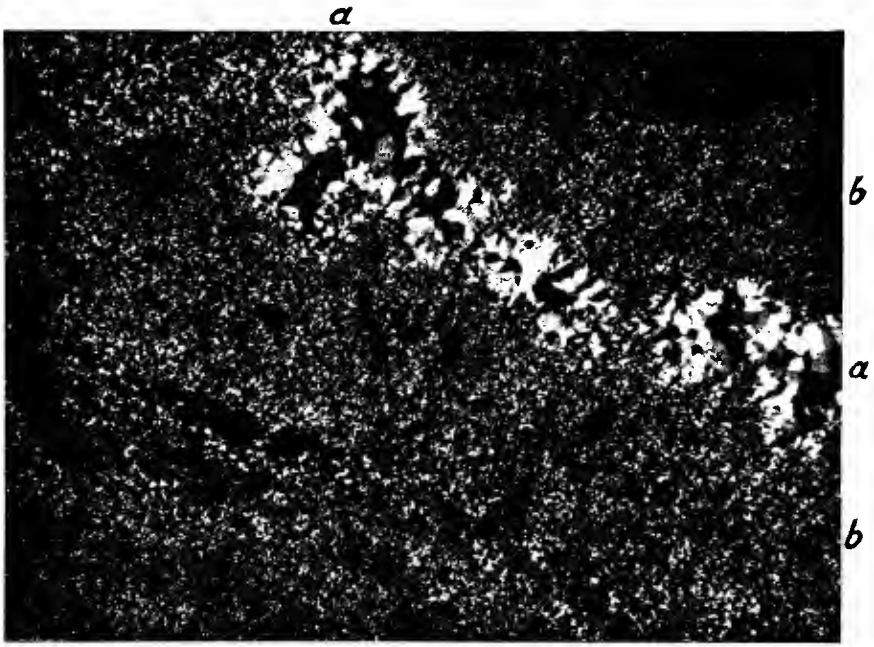

FIG. 112.—Alternating layers of quartz and chalcedony from the seleniferous gold lode at Redjang Lebong, Sumatra. Magnified 14 times. Collection, *Geol. Landesanst.*, Berlin.

dull, or it may be pronouncedly vitreous. The fracture too may be conchoidal or, especially when much chalcedony is present, it may be extremely fine-grained. Under the microscope, as illustrated in Fig. 113, lode quartz shows itself to be an aggregate of irregular and interlocked crystal individuals. Should a quartz lode cross slaty country in which older veins of non-auriferous quartz lenses occur, the experienced miner can tell at a glance whether any piece of quartz raised from the mine belongs to the one or to the other occurrence. The older quartz is often pure white and vitreous in lustre, its whole appearance being described by the English miner as 'hungry.'

Next to silica the carbonates are the most common gangue minerals,

especially those of calcium, magnesium, iron, and manganese. These do not always occur pure and each by itself, but more often together and in all proportions. Indeed the proportions between the carbonates of calcium, magnesium, and iron, especially in those deposits arising from the metasomatic replacement of limestone, are so various that practically all gradations between those carbonates are represented. The cases in which siderite occurs as gangue have already been given on p. 73.

Barite and fluorite come next in importance as gangue minerals.

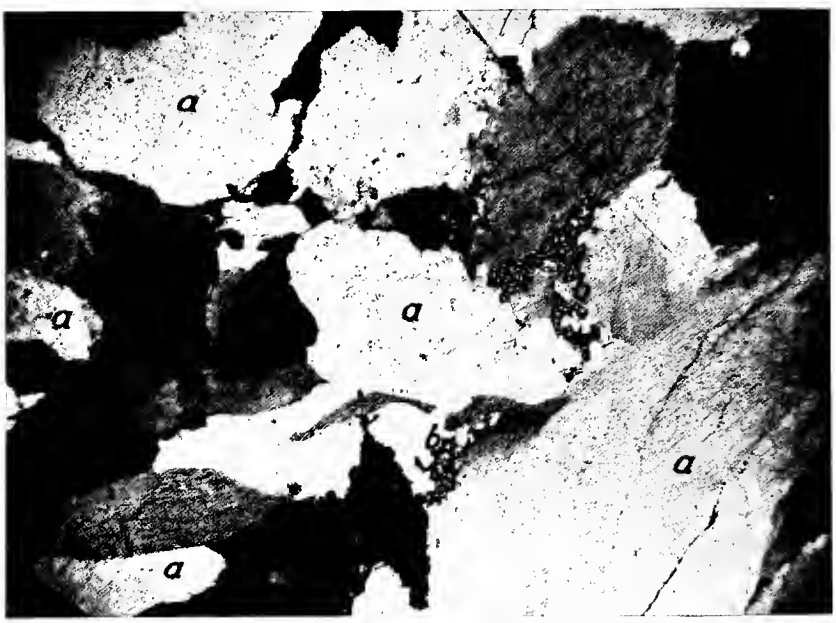

FIG. 113.—Lode quartz consisting of numerous irregular and interlocked crystal individuals. California. Magnified 14 times. Collection, *Geol. Landesanst.*, Berlin.

a, Quartz in polarized light; *b*, decomposed material.

Both these minerals are also found independently in deposits large enough of themselves to permit exploitation; but by far their wider occurrence is in small amounts in a large number of other deposits. Investigation with reference to these two gangue minerals has shown that they most frequently occur where two such solutions meet as contain sulphuric acid and baryta, hydrofluoric acid and lime, respectively. At such a meeting, in consequence of their insolubility, they become precipitated, although hydrofluoric acid and baryta, the characteristic components of the two precipitates respectively, exist only in traces in natural mineral waters. The occurrence therefore of barite and fluorite in ore-deposits proves that

frequency of occurrence is not proportional to the extent to which minerals exist in natural water, but rather to the extent to which they are insoluble.

The different gangues may be differentiated according to the effect of their presence during the subsequent processes of treatment, whether this effect be advantageous or disadvantageous. In general the miner and the metallurgist seek the removal of the gangue by concentration since the metal content in the ore to be treated becomes thereby correspondingly higher. While gangue which is disadvantageous in subsequent treatment is penalized, metallurgical works gladly accept a certain percentage of gangue which is advantageous. Large amounts of silica are never welcomed though carbonates on the other hand may, in those cases where other ores are siliceous, be of advantage in fluxing. Similarly while barite is strongly discountenanced, fluorite may under certain conditions be of advantage because being a good flux it assists the smelting. In the case of barite an exception perhaps may be made in the treatment of oxidized copper ores.

III. Rock Inclusions

These, the last of the materials forming a complete ore-deposit to be described, are the more or less altered portions of the country-rock which in one way or another have arrived within the mass of the deposit. With

Fig. 114.—Portion of a highly contorted lens of flucan from the Burgstadt lode-series near Clausthal. Collection, *Geol. Landesanst.*, Berlin.

fissure fillings these are generally pieces fallen from a collapsed hanging-wall; with beds they are fragments brought with the sand and slime into the ore-body by the action of water; in other cases, as for instance with metasomatic deposits, they are pieces of the country-rock not yet completely replaced; while finally with magmatic deposits they may be pieces of country-rock broken and enveloped by the molten mass at the time of its entry. A special case of these rock inclusions is that of slaty material termed

'flucan,' which when a lode crosses a slate country often constitutes the greater portion of its filling. This material, which as illustrated in Fig. 114 consists in greater part of country-rock intensely altered, occurs in masses irregularly distributed and disposed, and often having a lenticular shape due to the tremendous squeezing to which they have been subjected, while they themselves are also traversed by numbers of small mineral veins.

By the circulation of water along fissures standing more or less open, a portion of the country-rock often fritters away, especially when slates preponderate. A clay thus arises which settles again, particularly on the foot-wall, forming there a more or less greasy layer to mark the boundary between lode and rock. Such an occurrence as already mentioned is described as 'gouge.'

THE STRUCTURE OF ORE-DEPOSITS

Only exceptionally does an ore-deposit consist entirely of one ore. It is far more usual to find several ores occurring together with gangue minerals and rock inclusions, as illustrated in Fig. 85. The few cases of simple filling are therefore to be differentiated from those which are complex. The pyrite deposits of the Huelva district, illustrated in Fig. 115,

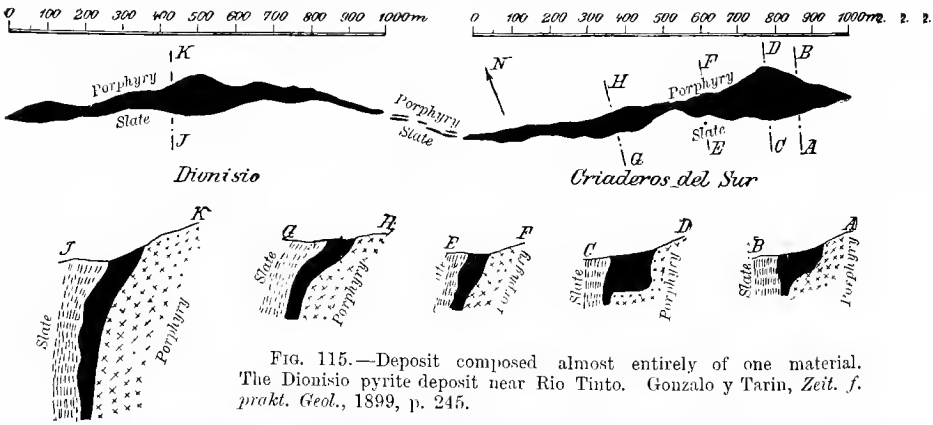

FIG. 115.—Deposit composed almost entirely of one material. The Dionisio pyrite deposit near Rio Tinto. Gonzalo y Tarin, *Zeit. f. prakt. Geol.*, 1899, p. 245.

when viewed macroscopically, are such simple fillings, as also are some beds of iron ore. When complex filling occurs, the intergrowth of the different minerals, that is the structure of the mass, demands a careful study not only in the interests of pure science but also because this structure is an essential factor in fixing the necessities which have subsequently to be met in dressing and treating the ore. In this connection the following structures are differentiated :

1. Irregular Coarse Structure

With this structure, larger and smaller aggregates of different minerals are so irregularly interwoven that it is not possible from their arrangement alone to fix their relative ages. This structure may take its shape either at the formation of the deposit or through the subsequent introduction of some of the components. The gold-bearing solutions for instance to which auriferous lodes owe their existence, generally carry at the same

Fig. 116.—Coarse intergrowth of pyrite (*a*), chalcopyrite (*b*), and quartz (*c*), from Bocheggiano, Tuscany. Magnified 4 times.

time large quantities of silica. From such solutions pyrite separates at points suitable to its precipitation while at other points quartz is deposited, both minerals presenting irregular outlines which becoming interlocked produce an irregular coarse structure such as is illustrated in Figs. 116 and 117. In this structure the gangue minerals and the rock inclusions may naturally also take part.

The circumstances with metasomatic zinc deposits are genetically different. In these deposits the processes of replacement, proceeding from fractures and bedding-planes, effect the alteration of only a portion of the limestone, the inside cores of the separate pieces often remaining unaltered though surrounded with ore. Should the shattering of the limestone be so

complete that a large number of these unaltered pieces appear, what may

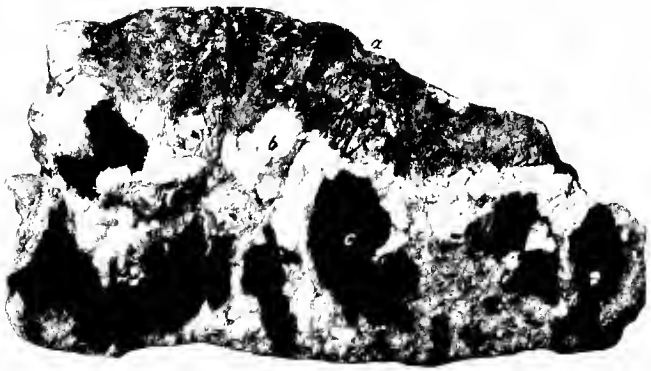

FIG. 117.—Coarse intergrowth of quartz (*b*), and wolframite (*c*), with lithiamica (*a*). Vereinigte Zwitterfeld mine near Zinnwald. Collection, *Geol. Landesanst.*, Berlin.

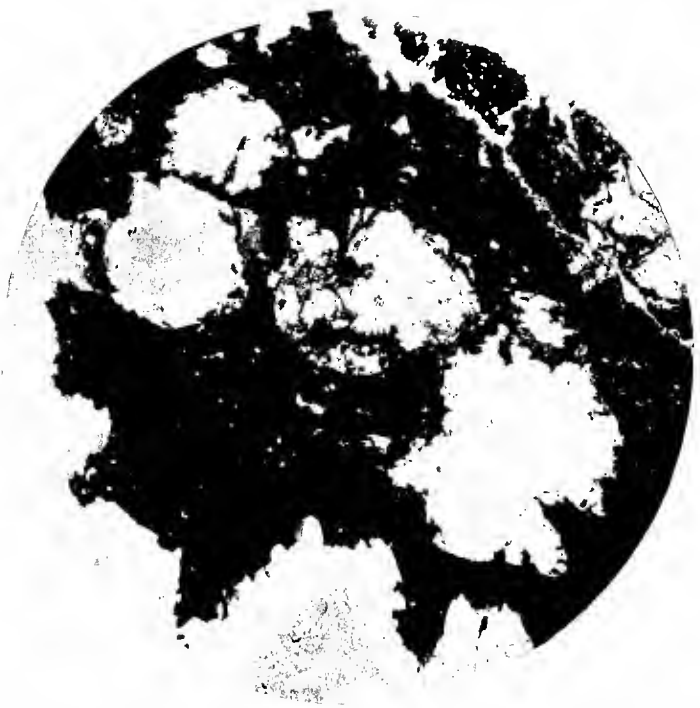

FIG. 118.—Secondary coarse intergrowth caused by the replacement of quartz (light) by sphalerite (dark). Siegerland. Magnified 14 times.

be termed a secondary coarse intergrowth of ore and limestone is presented. The same appearance is obtained when, as in the case illustrated in Fig. 118,

quartz is replaced by sphalerite. In the same manner an extremely resistant rock such as porphyry may become altered to manganese ore.

In cases where the components of a deposit having this structure are large enough they may be separated by hand-sorting, a condition which in ore-dressing is regarded as reflecting the most favourable circumstance.

2. Banded or Crusted Structure

With this structure, which is particularly characteristic of cavity-fillings, the several components of the filling are arranged in layers or crusts

Fig. 119.—Asymmetrical crusted structure, light dolomite (*a*), sphalerite (*b*), pyrite (*c*), light dolomite (*d*), sphalerite with rose-coloured dolomite (*e*), quartz (*f*). Himmelfurst mine near Freiberg. Double natural size. Collection, *Geol. Landesaust.*, Berlin.

and in regular sequence. When cavities become filled by deposition on the walls a layer lying nearer the wall is always older than one lying more centrally and upon the first. This relation in age may often be confirmed in lodes where the younger minerals have obviously grown upon the older. A banded structure however, as illustrated in Fig. 120, may also appear with magmatic segregations as when for instance pyrrhotite, chalcopyrite, and pyrite, occur in layers or streaks arranged alongside or over one another. In such a case there is no growth of younger layers upon older since all are contemporaneous. It may also even occur when only one mineral became segregated, if the bands of that mineral

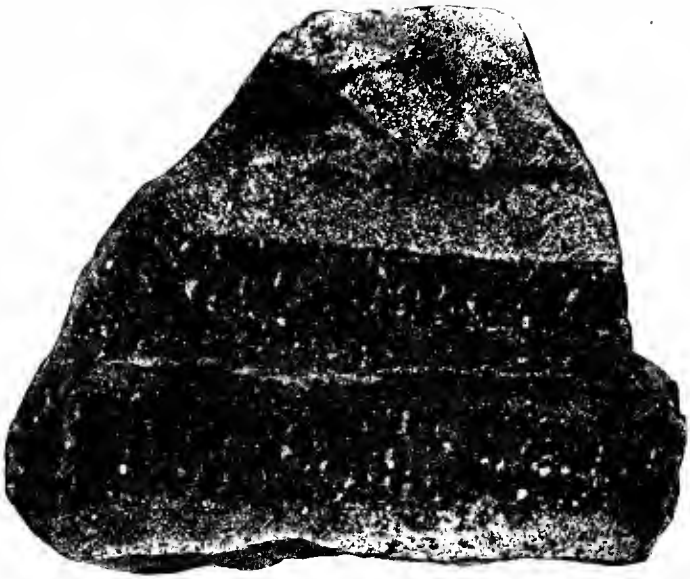

Fig. 120.—Banded structure formed by magmatic segregation. Two bands of pyrite (light) separated by eruptive rock in which nests of chalcopyrite are contained. Nieder-Sohland, Saxony. Magnified 2·5 times. Collection, *Geol. Landesanst.*, Berlin.

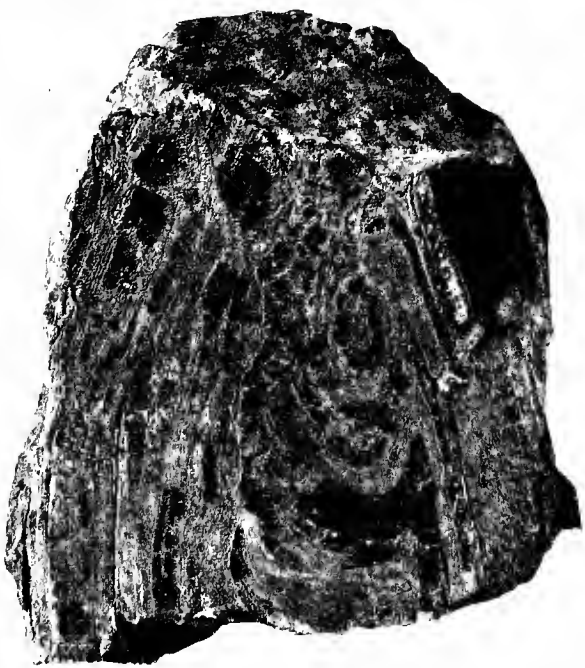

Fig. 121.—Banded structure with ore-beds. Itabirite from Krivoi Rog, South Russia, consisting of alternating beds of quartz (light) and hæmatite (dark). Collection. *Geol. Landesanst.*, Berlin.

are separated from one another by widths of more normal eruptive rock. Such an occurrence is illustrated in Fig. 1.

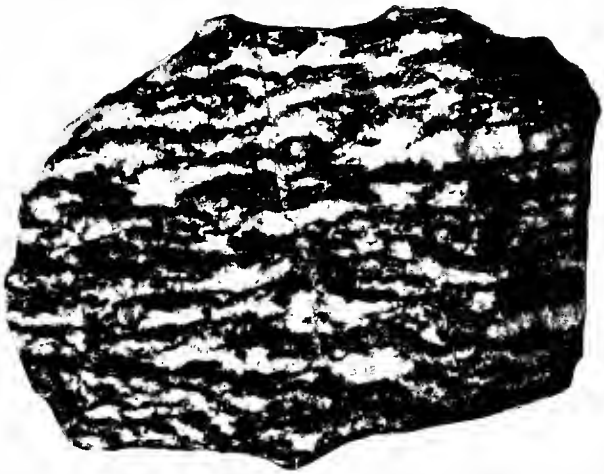

FIG. 122.—Magnetite (dark) and calcite (light) arranged in a banded structure produced by the replacement of certain peculiarly susceptible limestone layers. Schmiedeberg in Silesia. Collection, *Geol. Landesanst.*, Berlin.

Among ore-beds those known as itabirite are, as illustrated in Fig. 121, distinguished by a perfect banded structure in which innumerable thin quartz layers alternate continually with others of hæmatite. With metasomatic deposits this structure occurs when the original limestone was deposited in thin layers, some of which, probably the purest, became afterwards selected for alteration. In such cases, as illustrated in Fig. 122, the layers are alternately of metasomatic ore and unaltered limestone.

FIG. 123.—Symmetrical crusted structure of chalcopyrite (dark) and calcite (white) in hornblende-schist (grey) from Kupferberg in Silesia. One-half natural size. Collection, *Geol. Landesanst.*, Berlin.

This structure may occur in layers more or less even, when it is known as ordinary or plain crusted structure, or in concentric envelopes, when it is distinguished as concentric crusted structure. Ordinary crusted structure is formed when fissures are filled either by

the accretion of ore from one wall only, or from both walls at the same time. In the latter case the different layers towards one wall correspond with those towards the other and a symmetrical structure results in distinction to the asymmetrical structure corresponding to growth from one wall only. Concentric crusted structure may be formed in very different ways. It can be formed at the filling of an irregular but more or less round cavity when concentrated mineral solutions entering from above become distributed over the inside so that, as illustrated in Fig. 124, the materials crystallize regularly around the walls; every layer or crust on the outside is in such a case older than the one lying next to it on the inside; the filling of cavities occurring with metasomatic lead-zinc ore-deposits is especially characterized by this structure. Or again, when solution drops from the roof of a cavity,

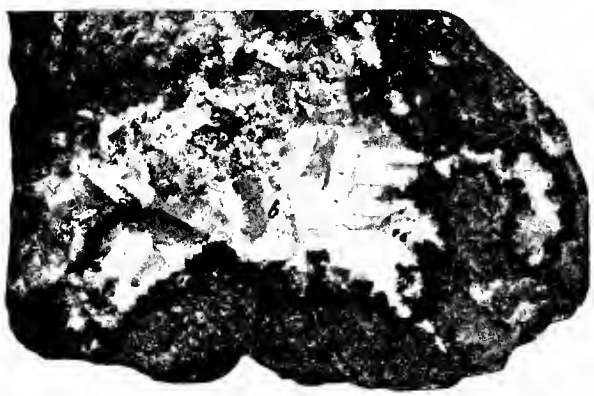

FIG. 124.—Crusted structure in a cavity-filling in melaphyre; laumontite (*a*), calcite (*b*). Oceola mine, Michigan. Collection, *Geol. Landesanst.*, Berlin.

the deposition may be in stalactitic form at the point of fall, with corresponding stalagmites below if the solution falls freely to the floor; such deposits, as illustrated in Fig. 125, also have in section a concentric crusted structure which differs however from that just described in that each layer on the outside is younger than the one lying next to it on the inside. And again, when cavities are partly filled with fragments of country-rock or when from a solution contained within an enclosed space mineral crystals separate and remain loose, younger minerals may be deposited in layers around such fragments or crystals; such concentric crusted ore, illustrated in Fig. 126, is known as 'cockade' or 'concentric ore'; with it every layer farther from the centre is younger than one nearer to it, an age-relation which is frequently characterized by the crystals pointing away from the centre. Finally, in many instances subsequent replacement of certain easily altered components of a deposit has taken place. If for instance the primary ore in spite of an apparent mineralogical uniformity

FIG. 125.—Concentric crusted structure of marcasite (*a*), with dark- and light-coloured schalenblende (*b*). Schmalgraf mine, near Aachen. 1·5 times less than natural size. Collection, *Geol. Landesanst.*, Berlin.

FIG. 126.—Concentric crusted structure. Fragments of country-rock cemented by quartz and each enveloped in an inner ring of galena (light) and an outer ring of sphalerite (dark). Burgstadt lode-series, Clausthal. Collection, *Geol. Landesanst.*, Berlin.

possessed a banded structure, and if the layers similar in material yet differing in age, differed also from one another in some physical or chemical

property, then in any subsequent replacement only such layers would be selected for alteration as were particularly suited thereto. This can be stated to have occurred for instance with the material of the Siegerland

Fig. 127.—Banded structure, resulting from the replacement of certain individual layers of siderite (light) by sphalerite (dark). Siegerland. Magnified 14 times.

siderite lodes, where the siderite was originally deposited in layers differing in colour and in their granular character, so that some only were afterwards replaced by sulphides. This occurrence is illustrated in Fig. 127.

The difficulty or ease with which ore having this structure lends itself to the subsequent processes of dressing depends upon the thickness of the

individual layers. If these are very thin the entire mass must be crushed and the difficulties which then arise are similar to those stated below to occur when ore and gangue are intimately intergrown. If on the other hand they are large enough, the structure may allow a separation of the ore by hand-sorting.

3. Brecciated Structure

Fissures and cavities do not long remain open without portions of the country-rock falling from the hanging-wall and the sides. Any deposit then becoming formed would result from the filling of the interstices between these fragments and the resultant deposit might well consist in greater

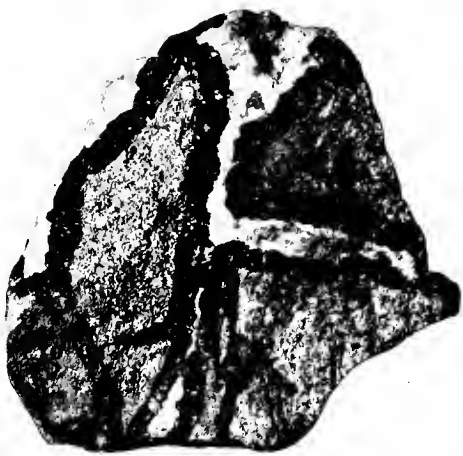

Fig. 128.—Brecciated structure. Fragments of arkose sandstone cemented by sphalerite (dark) and quartz (light). Schauinsland mine, Black Forest. One-half natural size. Collection, *Geol. Landesanst.*, Berlin.

part of fragments of country-rock. Such a structure in consequence of the angularity of the fragments is termed 'brecciated.' It is illustrated in Fig. 128. When describing cockade or concentric ore it was stated that with this the separate layers were arranged concentrically around fragments of country-rock; in consequence structures intermediate between this and the brecciated structure are not infrequent.

Although brecciated structure occurs most frequently with cavity-fillings, it may under some circumstances also occur with deposits of other genesis. For instance magmatic segregations may contain numerous pieces torn and broken from the wall. When, as is often the case, the angles of such pieces have not surrendered to fusion the whole occurrence is one of brecciated structure. Such an occurrence is illustrated in Fig. 129. A similar structure occurs when a rock prone to alteration, generally

limestone, is replaced by ore along cracks and fractures. While in the process of such change a compact ore-body represents the complete replacement of the limestone, the intermediate stages representing incomplete alteration often, as illustrated in Fig. 130, show angular pieces of the unaltered rock remaining. The difference between a brecciated structure thus resulting and the irregular coarse structure

FIG. 129.—Brecciated structure. Fragments of slate torn from the country-rock and enveloped in a magmatic deposit of pyrrhotite. Mug mine, Norway. Collection, *Geol. Landesanst.*, Berlin.

FIG. 130. — Brecciated structure formed by the replacement of porphyry along cracks by hard manganese ore. Oberhof, Thüringen. 1·5 times less than the natural size. Collection, *Geol. Landesanst.*, Berlin.

stated on p. 110 to have been similarly formed, is that the fragments of the brecciated structure are smaller and more closely compacted. Since with all occurrences of ore having this structure the proportion of rock in the ore mined is always considerable, in those cases where it is not desired to treat the material as a whole, a careful dressing of the ore is necessary.

4. Drusy Structure

The mass of a deposit is termed drusy when it contains many larger

or smaller cavities, the walls of which it is usual to find are adorned with stalactites, stalagmites, or crystals. Such a structure, illustrated in Fig. 131, may be either primary or secondary. It often proceeds hand in hand with alteration. With but few exceptions where alteration has occurred,

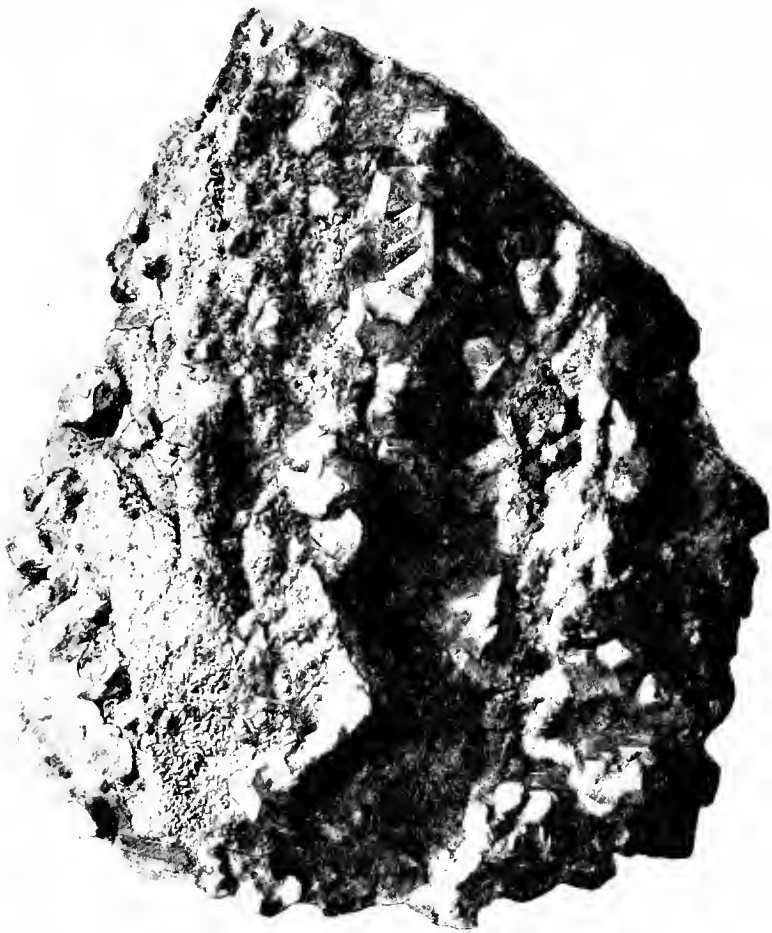

FIG. 131.—Primary drusy structure resulting from the incomplete filling of a fissure. Glückauf mine, near Velbert, Westphalia. Collection, *Geol. Landesanst.*, Berlin.

the newly-formed mineral occupies less space than the one replaced, and cavities remain which often have a stalactitic lining. This structure, as illustrated in Fig. 133, may also arise from the simple leaching of such ore or gangue as is easily taken into solution. The iron ores known as kidney and pencil ore, distinguished by a concentric and radial structure, are

especially characteristic of deposits with drusy structure, being in fact limited to such deposits.

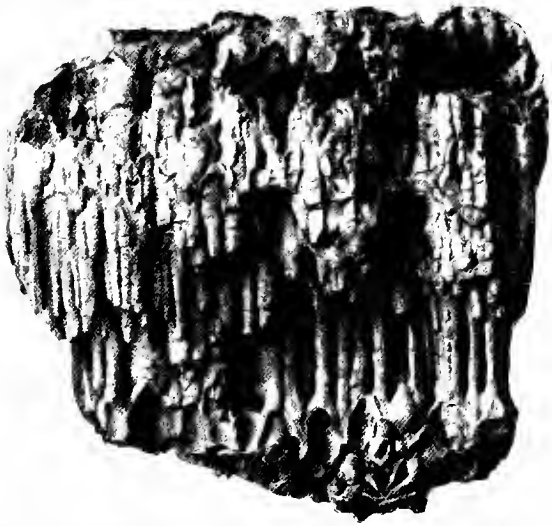

FIG. 132.—Stalactites of psilomelane exhibiting concentric scaly structure. Herdorf, Siegerland. Collection, *Geol. Landesanst.*, Berlin.

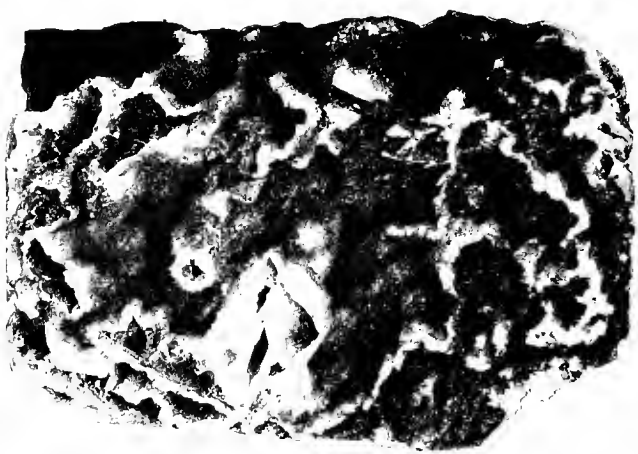

FIG. 133.—Drusy structure resulting from the removal of some of the original components by solution, quartz remaining. Spital Lode, Schemnitz. Collection, *Geol. Landesanst.*, Berlin.

5. COMPACT STRUCTURE

Under this term is understood that form of intergrowth in which the different mineral particles are so small that to the naked eye they appear inseparably and irretrievably mixed. To this class belong some mixtures

of galena and sphalerite, such for instance as those occurring at Argelèze-Gazost near Lourdes on the southern slope of the Pyrenees. Since to recover lead when zinc is present is metallurgically expensive and galena containing sphalerite is consequently paid for at a lower rate than when it is clean, this intimate intergrowth of the two ores is decidedly disadvantageous. For the production of a marketable product it demands the finest crushing of the material so that the whole may be concentrated when in the condition of slime, a necessity which brings with it a considerable

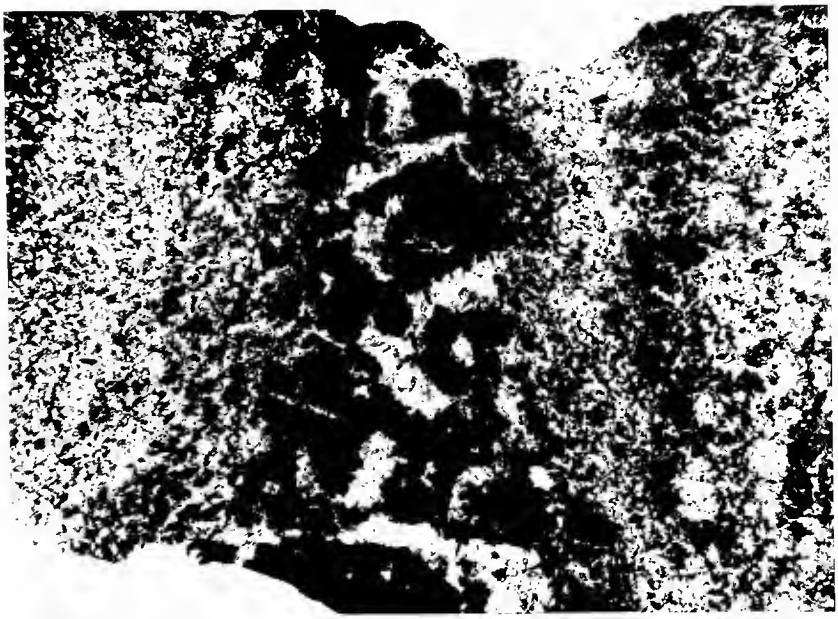

FIG. 134.—So-called brown ore, consisting of sphalerite and sulphides (dark) and bornite (light). Rammelsberg. Magnified 14 times.

increase in the working cost. Sometimes indeed with ordinary wet concentration it is not possible to achieve any result and to effect the desired separation it becomes necessary to use one of the magnetic or flotation processes. It may even be the case in countries where clean lead and zinc deposits are of more common occurrence, that large occurrences containing both ores mixed in this manner, are regarded as unpayable.

The lead-zinc occurrences of Broken Hill in New South Wales also belong to the class of compact ores, although the individual mineral particles are somewhat larger than those described in the paragraphs above and may even be large enough to connect this class of structure with that described as irregular coarse.

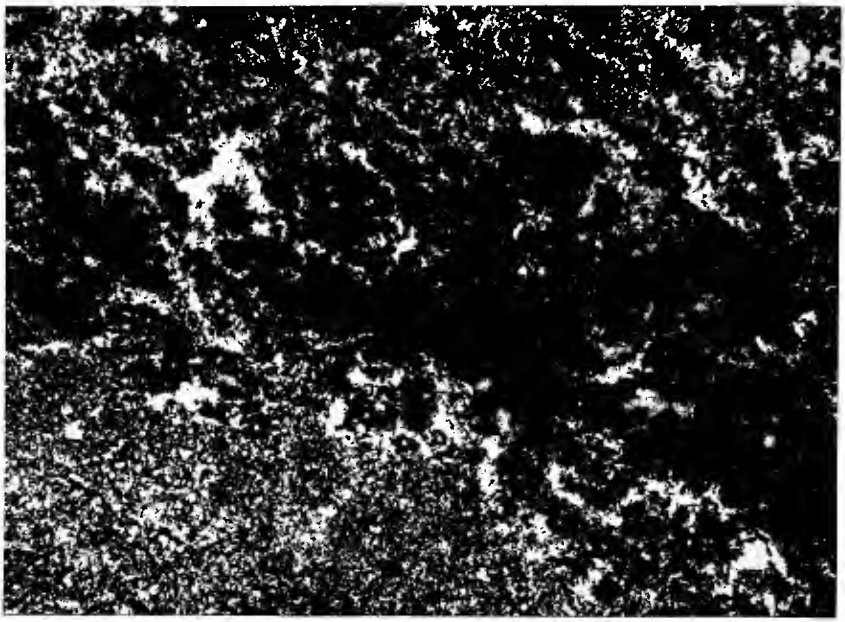

Fig. 135.—So-called grey ore, consisting of sphalerite and galena (dark) and bornite (light). Rammelsberg. Magnified 14 times.

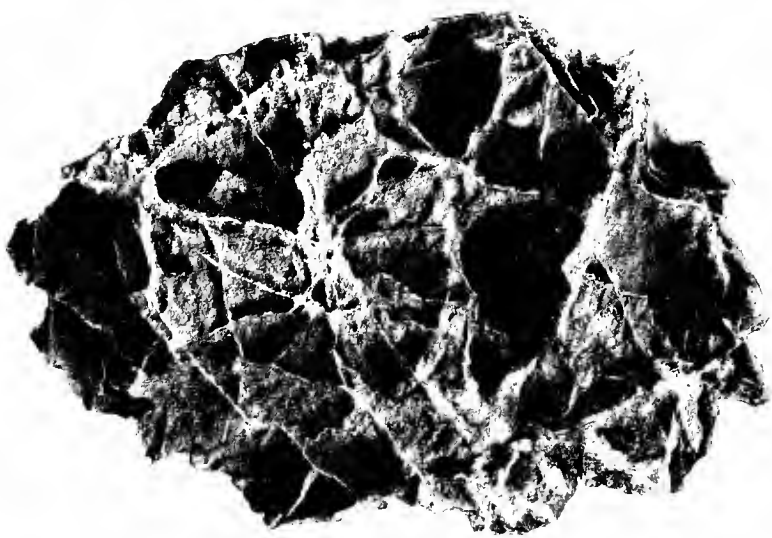

Fig. 136.—Drusy structure produced by secondary alteration. Cellular smithsonite from the Schwelm mine, Westphalia. Collection, *Geol. Landesanst.*, Berlin.

Microscopic Structure

Though the macroscopic structures just described have been fully investigated, the application of the microscope to the study of ore, on the contrary, is still in its infancy in spite of the advantages which this method of research undoubtedly possesses. Within late years the metallographic microscope has been used in the investigation of opaque ores and by its means much fresh information has been obtained. For instance the occurrence of pentlandite in microscopic proportions in nickel-pyrrhotite has been established, making it probable that the pyrrhotite itself has no nickel content.

It may be said as a rule that the microscopic features of ore-deposits

Fig. 137.—Drusy deposit consequent upon decomposition. Stalactites of malachite from the Urals. Collection, *Geol. Landesanst.*, Berlin.

are similar to the macroscopic, and that therefore the different structures just described, namely the coarse structure, the banded structure and the brecciated structure, become repeated. In many cases the examination of thin slides has a particular importance in that by its means it is often possible to determine the relative ages of the component minerals and thereby to satisfactorily settle the question of genesis. It may even be that safe conclusions relative to the character of the ore in depth may be drawn from such an examination.

Where, as illustrated in Fig. 138, mineral-bearing solutions have made their way into the same fissure at different times and have effected a replacement of some of the material first deposited, the microscopic investigation of thin slides will give reliable information concerning the sequence of deposition. In another direction, the microscopic structure will often

indicate the best line to adopt in the dressing and metallurgical processes, or it will assist to explain striking chemical determinations or apparent contradictions in analyses. For instance a sample of galena with abnormally high silver content of which no indication is afforded to the naked eye, may, as illustrated in Fig. 139, under the microscope show itself

FIG. 138.—Replacement of siderite and quartz along cracks by sphalerite. Holzappel mine, on the river Lahn. Magnified 15 times.

to consist of a mixture of galena and metallic silver, the latter filling the pores and fractures of the former. A structure such as that would indicate that the galena came from the cementation zone of an ore-deposit, and in itself would give warning that a quick and considerable impoverishment of the silver content below the ground-water level might be expected. Again, compact pyrite with a strikingly high gold content may present itself under the microscope as a mixture of metallic gold and pyrite, the noble metal filling the finest fractures and cracks of the pyrite. Such

strikingly rich ores, coming undoubtedly from the cementation zone of an auriferous deposit, do not continue into depth. And again by means of the microscope it may be found that an apparently solid piece of chalcopyrite does not by any means consist entirely of that mineral, but contains many kernels of unaltered pyrite. The structure thus presented, which would very much resemble that of olivine in the process of decomposition to serpentine, would indicate that the mass was originally pyrite, the greater

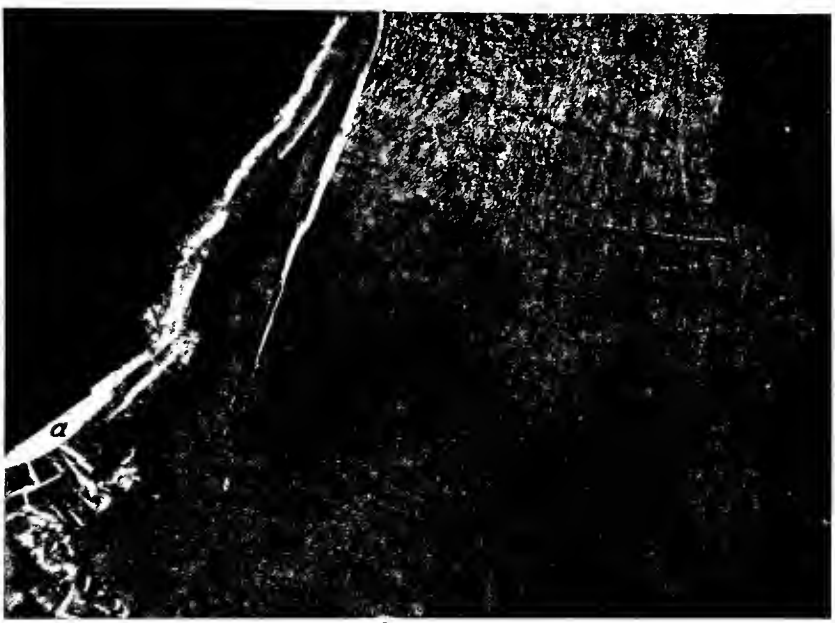

FIG. 139.—Metallic silver as white streaks (*a*), deposited along the cleavage-planes of galena (*b*). Mexico. Magnified 18 times. Collection, *Geol. Landesanst.*, Berlin.

part of which had subsequently become changed to chalcopyrite. Without doubt therefore such a piece of ore would have come from the cementation zone of an ore-deposit and its copper content would therefore not be taken as applicable to the primary zone which at the earliest could not be expected till under the ground-water level.

Finally, it must be particularly pointed out that the different structures may occur in all possible combinations. In a cavity-filling with crusted structure each separate layer may show coarse structure, while in a deposit with coarse structure a drusy structure may also occur.

MINERAL FORMATION

With Special Regard to the Formation of Ores and their Associated Minerals

LITERATURE

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Mineral-synthesis has received more particularly the attention of the French school which includes such workers as Becquerel, Berthier, Daubrée, Debray, Ch. and H. St. Claire-Deville, Durocher, Ebelmann, Gay-Lussac, Sénarmont, Troost; and more recently Bourgeois, Feil, Frémy, Friedel, Fouqué, Gorgeu, Hautefeuille, Lechartier, Le Chatelier, Macé, Mallard, Margottet, Meunier, Michel Lévy, Moissan, Offret, etc. Earlier investigators of this subject were Berzelius, Bischof, Breithaupt, Bunsen, Drevermann, Forchhammer, Fuchs, Gurlt, Hall, Haussmann, Hoppe-Seyler, Koch, Knop, Leonhard, Manross, Mitscherlich, Plattner, Rammelsberg, Rose, Sandberger, Vogelsang, Wöhler; while among those more recent, in addition to those given above, must be mentioned Bäckström, Becker,

Bruhns, Brun, Clarke, Friedländer, Holmquist, Hussak, Lemberg, Luzi, Oetling, Pratt, Rinne, Rössler, Schulten, Stelzner, Thugutt, Vater, Vernadsky and Weinschenk.

This branch of science has of late years taken a new direction in which the greatest importance is laid upon the investigation of the physico-chemical laws operative in the formation and alteration of minerals. Reference may be made to the well-known works by Van't Hoff and his collaborateurs upon the minerals of the salt beds, and to the following works chiefly concerning the silicate minerals :

J. H. L. Vogt. Die Silikatschmelzlösungen, Christiania, Ges. d. Wiss., 1903, 1904; Theori för smält slagg. Jern-Kon. Ann. Stockholm, 1905 ; ' Physikalisch-chemische Gesetze der Krystallisationsfolge in Eruptivgesteinen,' Tscherm. Min. u. Petr. Mitt., 1906 and 1908 ; Über anchi-monomineralische und anchi-eutektische Eruptivgesteine. Christiania, 1908.—Arthur L. Day and fellow-workers at the Geophysical Laboratory of the Carnegie Institute, Washington. A series of works, more particularly since 1905, upon the plagioclase-felspars, the minerals of the $CaO - SiO_2$ series and tetramorphie $MgSiO_3$, etc.—C. Dölter. Physikalisch-chemische Mineralogie, 1905 ; Die Petrogenesis, 1906. Further and especially since 1902, numerous articles by Dölter and his pupils upon the smelting points of minerals, etc.

In the following short summary, compiled with great assistance from Braun's *Chemische Mineralogie*, the results taken from that work as well as those from that of Fouqué et Michel Lévy are not specifically indicated.

The study of the genesis of ore-deposits can only be prosecuted with any promise of success when the fundamental principles of mineral formation are known. For the proper study of these principles there are more particularly two means available ; firstly, observation of those cases in nature where the formation of minerals is proceeding at the moment ; and secondly, experiment in the laboratory under conditions which give all possible consideration to those factors which in nature are active in the formation of minerals.

Mineral formation interests the student of ore-deposits in so far as it relates to ores and their associated minerals. In general, six manners of mineral formation may be differentiated.

1. Crystallization from Molten Silicate Solutions

The molten silicate solutions including both the water-free molten silicates of laboratory experiment and the water-containing eruptive magmas are, according to Vogt whose presentation of the subject is followed, to be regarded in general as mutual solutions of a series of components, these solutions being, when the water combinations are left out of consideration, chemically identical with those minerals which crystallize at solidification. When mix-crystals, olivine $(Mg, Fe)_2SiO_4$ for instance, are formed the different components, in this case Mg_2SiO_4 and Fe_2SiO_4, are to be regarded as independent components in the magmatic solution. Crystal-

lization from mutual magmatic solution follows the same physico-chemical laws as that from any other mutual solution, whether that of molten metals, of molten salts such as KNO_3 and $NaNO_3$, or of aqueous solution such as that of common salt. When mutual solution takes place—colloidal solutions not being here included—a lowering of the melting-point takes place at the same time until the so-called eutecticum is reached. With components independent of one another the sequence of crystallization depends in the first place upon the composition of the solution in relation to that of the eutecticum. The maximum lowering of the melting-point between H_2O and NaCl is $-22°$ C., this occurring when the proportion is as 23·5 per cent NaCl : 76·5 per cent H_2O, this relation of two substances representing the condition of a binary eutecticum. With more water in the original solution ice would crystallize first ; with more NaCl on the other hand it is the salt which would first separate. Similarly the eutecticum between olivine and diopside exists with 32 per cent olivine and 68 per cent diopside ; with more Mg_2SiO_4 in the solution olivine would crystallize first ; with more $CaMgSi_2O_6$ on the other hand diopside would be the first to separate. In addition however to these considerations the phenomena of supersaturation must be taken into account especially when cooling takes place quickly.

Just as with freezing-mixtures and with metal-alloys the components of which do not form mix-crystals with one another, so also is it the case with silicates, that the lowering of the melting-point at their mutual solution is considerable. Compelled thereto by physico-chemical causes which will not here be discussed, most of the eruptive rocks approach more or less closely to an eutecticum. Thus most granites, quartz-porphyries, and liparites, approach fairly closely to the eutecticum between quartz and the felspars ; the temperature interval at the crystallization of these eruptive rocks from their magmas is accordingly strikingly low. It may often happen that quartz which fuses at about 1625° C. first begins to crystallize at a temperature of about 1100–1200° C. Lavas from Vesuvius have been observed to be still in a molten condition at a temperature of 1100° C.

When mix-crystals solidify the laws developed by Roozeboom become operative as also among others does that of the decrease in solubility with a common ' ion.'

Experience shows that all silicates, fluorides, ferrates, etc., when in a fluid condition, are freely soluble in one another. Thus with magmatic segregations of iron ore, eruptive rock is found with all possible gradations of magnetite or titano-magnetite content, from less than 0·5 to 99 or even 100 per cent.

Among others the following oxidized ores crystallize from molten silicate solutions : magnetite, chromite, zinc-spinel, hæmatite, ilmenite.

corundum, and under certain conditions hausmannite, cassiterite, cuprite, etc. With regard to sulphides, those having the composition RS where R = Fe, Mn, Zn, Cu, etc., are, within the range of ordinary melting temperatures, soluble in molten silicates and especially in those which are basic. Such basic silicates for instance are capable of holding as much as 8 or 10 per cent of ZnS or MnS in solution which at subsequent solidification would crystallize as sphalerite or alabandite. In a similar manner sulphides such as pyrite, pyrrhotite, chalcopyrite, sphalerite, etc., may separate themselves from eruptive magmas. By experiment it has been shown that the mutual solubility of silicate and sulphide rises with the temperature and probably also with the pressure. It may therefore be taken that in highly heated magmas and under high pressure they will be freely soluble in one another. This question will be more fully discussed when describing the segregated sulphide deposits.

The occurrence of minute crystals of metallic copper in the so-called Muronaglass, and of nickel-iron and platinum in certain basic eruptive rocks, indicates that native metals under certain conditions can also be soluble in molten silicates. Carbon also is soluble to some extent in highly heated slags and in eruptive magmas from which, according to Friedländer and von Hasslinger, it may under certain conditions, separate as graphite and under others as diamond. The successful production of diamonds by Moissan resulted, as is well known, not from the solidification of molten silicates but from that of metal carbides. Eruptive magmas in addition to water contain carbonic acid, fluorides, chlorides, etc. The water contained does not in general come by descent from the earth's surface, but as will be mentioned later, it represents a primary increment from the interior. With effusive magmas flowing over the surface and eventually solidifying, the enclosed gases and vapours make their way in greater part direct to the open air. With intrusive magmas such as solidify slowly and under the pressure of considerable depth, the magmatic gases or vapours force their way partly into the neighbouring rock and partly into the already solidified portions of the magma itself. Such magmatic gases and vapours as these effect the formation of new minerals and the remodelling of others over large areas, so that in the study of ore-deposits they are of great importance.

2. Mineral formation by Sublimation

The expression sublimation is often wrongly applied in this connection to cases where mineral formation is actually due to gases or vapours. Strictly speaking, only those processes may be included under this term by which an already existing chemical combination becomes first raised by heat to the condition of a vapour and then afterwards deposited unaltered

at a different place, this deposition resulting either from a lowering of temperature or of pressure. Sublimation is therefore nothing but a special transference of certain minerals.

Many minerals can only be sublimed in the absence of oxygen that is in a so-called neutral atmosphere, since their vapours would be strongly attacked and decomposed by that gas. For this reason the oxygen in the air must be displaced by hydrogen or nitrogen before such minerals as sulphur, arsenic, galena, sphalerite, cinnabar, stibnite, greenockite, realgar, orpiment, arsenical and antimonial acids, and the larger part of the compounds with chlorine, etc., may be sublimed. In the electric furnace where temperatures of 3000° C. and more may be maintained, a whole series of elements and compounds long considered as comparatively difficult to fuse become, as Moissan showed, vaporized, as for instance iron, uranium, gold, platinum, and even silica and magnesia. In this furnace also quartz and zircon may be brought to the liquid state and even made to boil. Upon cooling, the vapours produced crystallize again as the original minerals.

3. Mineral formation resulting from the decomposition of Gases and Vapours by Heat

The phenomena attendant upon this process have been fully treated in the science of thermal chemistry. A simple example of minerals formed in this manner is afforded by the re-formation of carbon in the blast-furnace. Between carbon dioxide, carbon monoxide, and carbon, the equilibrium is expressed by the following formula: $2CO \rightleftarrows CO_2 + C$. At certain low temperatures the one part of carbon separates itself definitely, leaving one part of carbon dioxide, and the formula becomes $2CO = CO_2 + C$. Similarly, by heat heavy-carburetted hydrogen becomes separated into light-carburetted hydrogen and carbon according to the formula $C_2H_4 = CH_4 + C$. The so-called retort-carbon is formed in this manner.

4. Mineral formation by the mixing of two Gases

Numerous minerals which, apart from the possibilities of the electric furnace, cannot in themselves be sublimed, may be formed at the mixing of two gases. Gay-Lussac, as far back as the year 1823, produced specularite by the action of ferric chloride vapour upon water-vapour at a high temperature, thus $Fe_2Cl_6 + 3H_2O = Fe_2O_3 + 6HCl$.

In this connection the epoch-making sublimation-syntheses conducted by Daubrée in the late 'forties, continue to be freely cited. By the action of heated stannic chloride vapour upon water-vapour, this investigator produced cassiterite, the reaction being represented by the formula $SnCl_4 + 2H_2O = SnO_2 + 4HCl$. Rutile, crookite, corundum, magnetite,

zinc-spinel, etc., may be formed in a similar manner, while the chloride in this reaction may also be replaced by a fluoride. If sulphuretted hydrogen be taken in the place of water-vapour, the sulphide ores, galena, sphalerite, chalcocite, argentite, stibnite, bismuthinite, as was determined by Durocher in the year 1851, become formed, thus $PbCl_2 + H_2S = PbS + 2HCl$; or the sulph-antimonides and -arsenides such as tetrahedrite, pyrargyrite, and proustite, thus $3AgCl + SbCl_3 + 3H_2S = Ag_3SbS_3 + 6HCl$.

Sulphur itself is formed from the interaction of sulphuretted hydrogen and sulphurous anhydride, as well as from the incomplete combustion of sulphuretted hydrogen, the two reactions being respectively $2H_2S + SO_2 = 3S + 2H_2O$, and $H_2S + O = H_2O + S$.

Finally, siderite is formed when the vapours of ammonium carbonate and those of ferrous chloride meet, the equation being $(NH_4)_2CO_3 + FeCl_2 = FeCO_3 + 2(NH_4)Cl$.

5. Mineral formation by the Action of Gases or Vapours upon Solid Bodies

Here the action of the volatilized compounds of fluorine, chlorine, boron, and sulphur upon heated oxides, silicates, etc., is all-important. A whole series of minerals becomes thereby formed: apatite by the passage of phosphoric-chloride over heated acetate of lime; many sulphides such as galena, argentite, chalcocite, pyrrhotite, pyrite, chalcopyrite, etc., by the passage of sulphur vapours or sulphuretted hydrogen over heated metals or oxides. Wöhler, as early as the year 1836, produced pyrite by heating iron-oxide with sal-ammoniac and sulphur; also a whole number of oxides, such as cassiterite, rutile, specularite, corundum; and many silicates as for instance willemite, this latter mineral by the action of silicon fluoride upon zinc-oxide. The mineral orthoclase has long been known to be produced in blast-furnaces in those cases where fluorspar in quantity is added as a flux, this fact having been pointed out by Haussmann in 1810 and by Freiesleben in 1834. Quartz, magnesia-mica, and leucite, may also be formed under similar circumstances.

Friedel and Sarasin in 1887 produced good crystals of topaz by heating silicon-fluoride at a constant temperature of 500° C. with a mixture of kieselguhr and alumina in the presence of water.

Many sulphide ores have been produced by the action of sulphuretted hydrogen upon metals, or upon solid metal oxides or chlorides. Among these argentite may be formed by sulphuretted hydrogen acting upon metallic silver, this fact being particularly interesting since superheated steam will reduce the argentite to metallic silver again. The horns of native silver which, as illustrated in Fig. 140, occur at Kongsberg and have been

closely studied by Vogt, have undoubtedly arisen through such a decomposition of argentite. Similarly as was demonstrated by Bunsen and Geitner, if iron oxide or basalt powder be long heated under pressure and in the presence of SO_2, pyrite is formed.

Mineralizing Agents.—Elie de Beaumont and H. St. Claire-Deville termed all those substances, such as water-vapour and volatilized fluorine, chlorine and boron combinations, which in the above-mentioned way play an important or decisive part in the formation of minerals, 'agents minéralisateurs,' which may be translated 'mineralizing agents.' This expression as Morosewicz pointed out in 1898, is however not quite apt, more particularly because the action of the fluorides, etc., must frequently be regarded as catalytic.

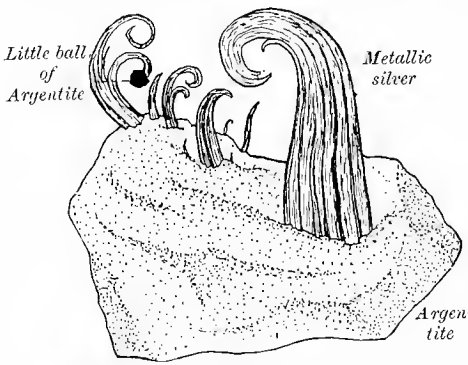

Fig. 140.—Horns of metallic silver arising from argentite. Vogt, *Zeit. f. prakt. Geol.*, 1899, p. 115.

The phenomenon of the formation of corundum, the crystallized oxide of aluminium, by the passage of hydrofluoric acid and water-vapour over the heated amorphous variety of the same oxide, rests upon the fact that aluminium fluoride and water are first formed, which reacting between themselves, produce corundum, the two stages being expressed in the formulæ: (1) $Al_2O_3 + 6HF = Al_2F_6 + 3H_2O$; (2) $Al_2F_6 + 3H_2O = Al_2O_3$ (corundum) $+ 6HF$. With the completion of this cycle the hydrofluoric acid is free to play its part again, so that a small amount of this acid would serve to produce a large amount of corundum.

Pneumatolysis.—All those processes of mineral formation in which gases and vapours play an important part, were included by Bunsen under the term 'pneumatolysis.' In those cases where in addition to gases and vapours aqueous solutions contributed to the result, this enlarged process was termed 'pneumatohydatogenesis.' As will be seen however from the following considerations, there is often in nature no sharp boundary between these two processes. Many gases can be liquefied by the application of high pressure, though in each case this can only take place below a fixed temperature which is known as the 'critical temperature.' It is thus impossible to liquefy carbon dioxide above 31° C.; hydrogen-chloride above 52° C.; and sulphuretted hydrogen, sulphur dioxide, carbon monoxide, chlorine, and ammonia, above 200° C. Above the critical temperature however the

physical differences between the gaseous and the liquid condition which may exist at a lower temperature, are no longer found. The critical temperature of water, 375° C., is especially important in relation to pneumatolysis and pneumatohydatogenesis. Since above this temperature even under the highest pressure there exists no longer any difference between the liquid, the vaporous, and the gaseous condition of water, and as with the gaseous processes in nature high temperatures must generally be considered to have obtained, the ordinary conception of the frequency of aqueous solutions is untenable. Further, with such high temperatures the difference between pneumatolysis and pneumatohydatogenesis disappears.

Mineral formation by pneumatolysis takes place in nature principally around volcanoes. The exhalations of these have been carefully studied by Elie de Beaumont, Bunsen, St. Claire-Deville, and Fouqué ; while Scacchi, Sylvestri, Palmieri, St. Claire-Deville, Heim, Lemberg, vom Rath, Roth, Sartorius, Wolf, and many others, have concerned themselves with the resultant minerals, especially those found occurring around Vesuvius, Monte Somma, Etna, the island of Santorin, the Laacher See, and in Iceland, etc. Those exhalations which consist chiefly of water-vapour with such gases as nitrogen, hydrogen, free hydrochloric acid, hydrofluoric acid, and silicon fluoride, are termed ' fumaroles ' ; those characterized by sulphur combinations are similarly ' solfataras ' ; those consisting chiefly of carbon dioxide are ' mofette ' ; while finally those with boric acid vapours are termed ' soffioni.' It is only in but few cases that the exhalations from the magmas of modern volcanoes have formed useful deposits. The solfataras are responsible for occurrences of native sulphur in volcanic craters, while the soffioni have formed deposits of boric acid of which the best known are those of Volcani, one of the Lipari Islands, and those of Sasso in Tuscany. In smaller amounts chlorides, especially those of the alkalies, calcium, iron, manganese, aluminium, lead, and copper, are found on the bottom and sides of craters, in the cracks of lava streams, and upon the bombs ejected. Tin and cobalt minerals occur occasionally, but in still smaller amount ; while the oxychloride of copper and some sulphates and fluorides must also be mentioned.

The intensity with which mineral formation by pneumatolysis may proceed in nature, was illustrated by the filling of a crack in lava poured out from Vesuvius in 1817. By the action of the ferric-chloride vapour upon that of water, this fissure became so rapidly filled with specularite that in 10 days a width of 3 feet was completed.[1]

Concerning the sequence in which the gases are exhaled from magmas, the data collected by Ed. Suess are interesting. From the upper surfaces of cooling lava streams the hottest fumaroles, that is those over 500° C.,

[1] Breithaupt, *Paragenesis der Mineralien.*

are dry, but usually contain compounds of chlorine, HCl, and NaCl, together with those of fluorine, boron, and phosphorus. As the temperature falls the gases characteristic of the fumaroles likewise diminish, while sulphur, arsenic, and carbon dioxide, become more important. With further cooling the carbon dioxide continues after the others have failed and is still found in exhalations from lava in a very advanced stage of cooling.

Pneumatolytic Metamorphism of the Country-Rock.—The gases escaping from volcanoes, especially sulphuric acid, sulphurous acid, sulphuretted hydrogen, hydrochloric acid, etc., effect not only the formation of minerals in open spaces, but also occasionally bring about an intense alteration of the country-rock, such alteration being known as 'pneumatolytic metamorphism.' The sulphuric acid arising by the oxidation of the sulphuretted hydrogen as well as the sulphurous acid, attack most energetically the neighbouring eruptive rock, tuff, etc., with the formation of alum minerals, aluminium sulphate, selenite, etc.; and it would also appear that, at the same time, at least a portion of the silica is removed in solution.

As will be mentioned later in the chapter dealing with th eorigin of ore-deposits, one entire group namely that of the tin lodes, is due entirely to these pneumatolytic processes, this origin having been ascribed to them by E. de Beaumont and by Daubrée as far back as the 'forties of the last century. The minerals associated with this group are distinguished by containing fluorine or boron, the former in such minerals as fluorite, lithia-mica, topaz, and fluor-apatite; while the latter is chiefly represented in tourmaline. This group of deposits is also characterized by a very definite metamorphism of the country-rock this in most cases being granite. By pneumatolytic processes the felspar and mica of this rock have become replaced by quartz, tourmaline, topaz, lithia-mica, cassiterite, etc., until the resultant rock, termed greisen, consists entirely of quartz, tourmaline, topaz, cassiterite, etc., and has an appearance which has led in more cases than one to it being wrongly regarded as a quartzite.

Another important alteration which some primary rocks may undergo as the result of pneumatolysis, is that known as 'propylitization.' This alteration is to be observed with most of the gold-silver lodes which make their appearance in close connection with young eruptive rocks, and it consists in the secondary formation of chlorite, clay material, calcite, pyrite, etc. The alteration of the primary eruptive rock is often so complete that Richthofen in his time, failing to recognize the connection, regarded the rock now known to be altered, as a special eruptive rock marking the first effusion from the magma; and he named it propylite. In addition to propylitization it is usual to find with this group of lodes a certain amount of kaolinization, the characteristic result of the decomposition of felspar.

Pneumatolytic processes may also be responsible for the cryolite deposits of Greenland, the titaniferous lodes of the Alps, the Scandinavian apatite lodes with their well-defined scapolitization of the country-rock, and the fluorine and boron minerals in the syenite-pegmatite dykes of southern Norway.

6. Crystallization or Precipitation from Aqueous Solution

For the proper understanding of mineral formation in nature, the idea that concentrated solutions are necessary for the precipitation of mineral masses in a comparatively short time, must be abandoned. It is better to proceed from the idea that weak solutions only were operative in the formation of ore-deposits, and that in most cases these continued their activity unbroken for a great length of time. This procedure may be seen in progress in nature at the present time.

The mineral-bearing solutions which have to be postulated are, generally speaking, none other than the familiar springs. These Ed. Suess divided as follows : [1]

(*a*) Sweet springs, which flow away at an average ground-temperature and which in greater part contain carbonates. Suess termed these springs which take part in the surface-water circulation, ' vadose ' springs, to distinguish them from those he termed ' juvenile,' which represent new material brought to the surface from out of the earth's interior.

(*b*) Bitter springs, which differ from the previous class only by reason of their mineral content, which may cause the water to be described as saline, iodic, or bitter. These springs are likewise vadose and register a medium ground-temperature.

(*c*) Natural baths, which are those vadose springs having a higher temperature due either to a rise in the underground isotherms or to considerable difference in height between source and discharge.

(*d*) In contrast to these vadose springs there exists a series of thermal springs whose temperature does not vary with the season of the year, and which must have a juvenile or magmatic source. In spite of the high temperature by which they are distinguished, these have not always a high mineral content, but may occasionally consist of practically pure water. To this class the hottest springs of Europe belong. They are often found in direct connection with quartz lodes and sometimes even now they deposit such minerals as barite, pyrite, fluorspar, and galena. Examples well-known and of particular interest to the student of ore-deposits are those encountered in the Comstock Lode and at Redjang Lebong in Sumatra.

(*e*) Geysers or intermittent springs, which are also juvenile and which

[1] ' *Über heisse Quellen*,' *Verh. Ges. deutsch. Naturforscher und Ärtze*, 1902, I.

may be regarded as connected with the later stages of a previously more active vulcanicity.

Without examining the basis for this classification it is only necessary here to call attention to the fact that in nature at all events, no sharp line may be drawn between vadose and juvenile springs, and that transitions and mixtures of both occur, especially where different fissure-systems meet.

From these natural mineral-bearing solutions, minerals may be deposited under the following varied circumstances.

(*a*) By Dissipation of the Medium of Solution.—When water evaporates the solids contained in it must naturally be deposited. The same effect is produced when the medium whereby a compound not otherwise soluble is kept in solution, is withdrawn. The present deposition of cinnabar at Steamboat Springs in California and at Sulphur Banks in Nevada, depends upon the fact that the sulphide of mercury is not soluble in pure water but only in a solution of alkaline sulphides. When therefore a solution containing both arrives at the surface, the alkali sulphide becomes decomposed by the carbonic acid of the atmosphere and the mercury sulphide being no longer soluble is precipitated from solution. The formation of sulphur at many hot springs, as at Aachen, Burgbrohl, and that of orpiment and realgar at the geysers of Yellowstone Park, may be similarly explained.

It is a well-known fact also that many carbonates only become soluble in water when free carbonic acid is present; should this substance for any cause whatever vanish or escape, such compounds must fall out of solution. In this manner the carbonates of the alkaline earths, calcium, strontium, barium, magnesium, and of zinc, manganese, iron, lead, and silver, may be formed. From experiments made by Chr. A. Münster it was determined that the carbonate of silver is even more readily soluble in water containing carbonic acid than calcium carbonate, a fact which may explain the frequent occurrence of carbonates, especially calcite, with native silver and rich silver ores.

With all such carbonates the solubility increases with the pressure. Temperature occasionally has a decisive influence upon deposition from solution. Calcite for instance, crystallizes from a cold solution when the solution is pure or when it contains an alkali silicate. On the other hand aragonite, the rhombic form of calcium carbonate, is formed when the solution is warm or when it contains lead, barium salts, or gypsum. The 'Sprudelstein' of Karlsbad, the oolitic 'Erbsenstein' and the 'Eisenblüte' of Erzberg in Steirmark, consist not of calcite but of arragonite, this doubtless being partly due to the impurities present in the original solutions. An important influence of temperature may be observed in the deposition of silica from an aqueous solution; at a higher temperature, which according to Dölter's experiments must not be lower than 180° C.,

and under pressure, quartz separates, whereas under all other conditions amorphous silica, opal, and chalcedony appear.

Iron and manganese only separate as carbonates from solutions containing carbonic acid when the atmosphere is completely excluded or when its oxidizing effect is neutralized by a reducing agent. Under any other circumstances the hydrate appears or, according to Senarmont, with higher temperature, the anhydrous oxide. Smithsonite and cerussite of recent formation have repeatedly been observed to occur in mines.

When a solution containing the carbonates of calcium, iron, and manganese, together with silicic and phosphoric acids, etc., loses its carbonic acid and at the same time becomes oxidized, the different substances separate in a regular order which will be more fully discussed when describing the origin of bog- and lake-iron ore. Many zeolites, such as apophyllite, natrolite, heulandite, chabazite, etc., have, according to Wöhler, Dölter, and others, been produced experimentally at temperatures ranging from 125° to 200°. That zeolites originate from hot solutions is confirmed by their occurrence in nature where they are usually found in close connection with eruptive rocks or with lodes which have undoubtedly been filled by hydro-thermal processes.

(*b*) By the Meeting of two Solutions.—Minerals which are with difficulty soluble do not take long to become formed and to be precipitated when two different solutions containing their components meet. The formation of barite in the Rhine-Westphalian district for instance attracted great attention last year in that, even where barium could only be found in traces in one of the two solutions, large amounts of barite nevertheless became deposited in the pipes and interfered with the working of the pumps.

The numerous springs occurring in Westphalia though all vadose allow themselves to be classified in the following groups, each of which is characterized by a particular acid. The bases are practically the same throughout with the exception of barium, which plays a rôle apart and occurs separately. The characteristic features of the separate groups are: (*a*) H_2SO_4 and HCl; (*b*) CO_2 in combination, H_2SO_4, and HCl; (*c*) HCl and Ba; (*d*) HCl in very small amount and small amount of bases, but often much free CO_2. Analyses of the water from the streams in the neighbourhood show that this water agrees very well with that of the first three groups, which is what might be expected from the fact that where the coal formation occupies the surface, these streams are fed from springs emerging along fissures. Though the amount of barium is but small the formation of barite at the meeting of two solutions containing barium and sulphuric acid respectively, is intense.

Fluorite according to Becquerel, is formed in the same manner by the

prolonged contact of two weak solutions of ammonium fluoride and calcium chloride respectively. The minerals found in the gossan of an ore-deposit and those characteristic of the oxidation zone are also all included in this class. Among such minerals are celestine, anglesite, cerussite, malachite, azurite, crocoisite, pyromorphite, mimetite, libethenite, cerargyrite, bromargyrite, iodyrite, etc. With each of these the very minutest quantities of its components contained in one or other of the solutions, are sufficient to bring about its formation. It may therefore be said that the frequency with which a mineral may occur depends not only upon the quantities in which its components are contained in the solutions concerned, but also upon its tendency to precipitation and to re-solution.

It occasionally happens that when two solutions mingle a reducing action arises. In this connection an old experiment by Bischoff is worthy of mention, wherein this investigator preserved a sealed mixture of sodium sulphate and ferrous carbonate for years, to find eventually upon opening it that pyrite had been formed. When a solution of ferrous sulphate meets with another which is auriferous native gold becomes precipitated, the result of its reduction from combination. This reaction plays a considerable part in the formation of the oxidation zone of gold deposits, a subject more closely discussed in the chapter dealing with the secondary depth-zones. It is to this class also that the recent deposition of gold in the siliceous sinter of Mount Morgan and of Steamboat Springs would appear to belong.

(*c*) By the Action of Gases upon Mineral Solutions.—In this manner carbonates and silicates among others may be formed. When free carbonic acid from whatever source comes into contact with a solution circulating in a fissure and containing a metal the carbonate of which is not readily soluble, the formation of this carbonate on a large scale takes place however weak that solution may be. Sulphuretted hydrogen under similar circumstances causes the formation of the heavy-metal sulphides.

When these latter are precipitated under ordinary temperature and pressure they are amorphous, whereas at a higher temperature and under a greater pressure, or by slower precipitation, they assume the crystalline form. In this way Sénarmont in 1850, Becquerel, Dölter, Weinschenk, and others, produced a whole series of crystalline sulphides, such as pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, stibnite, cinnabar, pyrargyrite, stephanite, etc. In most of their experiments temperatures between 100° and 300° C. were used, though under favourable conditions some were successful even at the ordinary temperature. With some sulphides the separation in crystalline form results, comparatively speaking, more quickly; thus the green crystalline sulphide of manganese, alabandite, often forms

one or two days after the addition of yellow ammonium sulphide to an ammoniacal manganese solution.

(*d*) By Electrolytic Precipitation.—Small scales of metallic silver are occasionally found covering native copper, an occurrence which may be explained to be the result of galvanic precipitation according to the formula $Cu + Ag_2SO_4 = Ag_2 + CuSO_4$. Nevertheless by far the greater number of the occurrences of native metal, according to all observations to date, have not resulted from electrolytic precipitation but have been formed in some other manner. It must however be remarked that in regard to mineral formation the importance of the electric currents streaming through the earth's crust has hitherto been but little studied.

(*e*) By the Action of Solid Bodies upon Solutions.—In the first place the reducing action exercised by minerals already formed must be mentioned. This action comes into consideration more particularly in connection with the noble metals and others which have but little affinity for oxygen; the lower this affinity the more easily does the metal concerned separate in its solid form. The reducing effect of a piece of pyrite, chalcopyrite, or galena, is for instance sufficient to precipitate metallic gold and silver from their solutions; while mercury, bismuth, copper, and lead, may also be precipitated by the addition of a reducing agent sufficiently strong.

The chemical-geological processes operative in nature are however in general not strong enough to precipitate from aqueous solution those metals which have a still greater affinity for oxygen. Iron and nickel indeed do occur native, but almost exclusively as magmatic segregations in eruptive rocks and never as precipitates from aqueous solution. Platinum, a noble metal, appears to occupy a singular position in that it has never yet been found in deposits originating from aqueous solutions, but exclusively in magmatic segregations. The explanation of this will probably be that platinum only very exceptionally goes into solution, while the other noble metals are comparatively much more readily soluble. Gold for instance may be dissolved in aqueous solutions of ferric sulphate, sodium silicate, sodium carbonate, sodium iodate, or it may be taken up in chlorine-water.

According to experiments by Skey, Newberry, Liversidge, and more recently by Münster, Johannsen, Stockhausen, and Krusch, all the natural sulphides such as pyrite, sphalerite, stibnite, chalcopyrite, galena, etc., precipitate gold and silver in a relatively short time from any of their solutions, while millerite precipitates bismuth from its sulphide solutions. In these experiments it was seen that with concentrated solutions the gold precipitated was often brown and earthy, while the silver precipitate was flocculent. The weaker the solution and the longer the time taken, the greater the resemblance of the precipitate to the actual occurrences in ore-deposits. The metallic gold, silver, copper, and perhaps also the bismuth

found in the crevices and cracks of galena and other sulphides in the lodes at Schneeberg, may in this way be explained. Such occurrences as these appear particularly in the cementation zone above the ground-water level. The mineral-bearing solutions formed by the action of the atmosphere upon deposits coming to the surface, continue their work of decomposition into depth only so long as the oxygen and the atmospheric salts are not yet consumed. As soon as this is the case the sulphides in the deposit act reducingly in the manner described above, and gold, silver, and copper, may be deposited in amounts which in time might become considerable.

Not only the sulphides but also the metals themselves may behave reducingly towards others in solution; in such cases the metals of higher affinity for oxygen precipitate those of lower affinity. In other cases the action of carburetted hydrogen, bitumen, or of ferrous compounds, suffices to precipitate metals having a low affinity. In this manner metallic copper is found on rotten mine timber; or together with metallic silver, along the bedding-planes of the well-known bituminous *Kupferschiefer*; or along the cleavage-planes of hornblende, etc. At Kongsberg also, metallic silver occasionally appears along the cleavage-planes of anthracite and garnet. The occurrence of metallic lead in the manganese deposit at Längban in Sweden is regarded by Hamberg as a precipitation by means of arsenic acids.[1]

Not only metals but metallic sulphides also may be precipitated by the reducing action of organic substances or of sulphides; pyrite for instance is frequently found upon timber in old workings. In this connection an experiment of Ochsenius is interesting. A piece of flint placed by this experimenter in a peat bog quickly became covered with a thin layer of pyrite resulting from the reducing action of the peat upon the ferrous sulphate present. Marcasite and sphalerite can also be formed in this manner.

The precipitation of sulphides and of sulpho-salts by older sulphides is of especial importance, because, in addition to the ordinary sulphides, pyrite, marcasite, galena, and sphalerite, the eagerly sought rich sulphides, bornite, chalcopyrite, and tetrahedrite, etc., may be formed in this way. As mentioned when considering the native metals, these sulphides, generally speaking, are always found where the surface waters have been in a position to effect the decomposition and alteration of an ore-occurrence. An interesting example of the formation of galena is afforded by a deposit in Missouri where fairly coarse galena occurs cementing and encrusting the fossil bones of *Mastodon* and *Elephas*. No less interesting are the crystals of pyrite, sphalerite, and chalcopyrite, which are often to be observed within the air chambers of cephalopods. The secondary formation of minerals upon old coins is another instance of the action of solid bodies upon solutions.

[1] *Zeit. f. Kristallogr. u. Mineralogie*, Vol. XVII., 1889.

Many oxides and hydrates may also be directly precipitated from solution, as for example limonite, manganite, hæmatite, the arsenical and antimonial oxides, and cuprite. According to Friedel, corundum and diaspore are similarly precipitated at a temperature between 400° and 500° C.; and according to Bruhns, magnetite and ilmenite at 300° C., after the addition of some fluoride. This fact, especially in so far as it relates to magnetite and ilmenite, is important, because it indicates that these two minerals which it is customary to find as magmatic segregations or in the form of ore-beds, may also occur in lodes.

(*f*) By the Action of Solutions upon Minerals.—The formation of minerals in this manner is generally speaking, found to occur with contact-metamorphism, pressure-metamorphism, and the processes of weathering. Of all the changes which take place in these different processes, the most interesting to the student of deposits is the rearrangement of the heavy-metal compounds to form new minerals.

(*a*) *Contact-metamorphism.*—Hot magma exercises in the majority of cases great physico-chemical action upon the neighbouring rocks. The zone subjected to this action having its boundary more or less parallel to that of the solidifying mass, is known as the 'contact-zone.' Limestone rocks within this zone become altered to a product quite different from that resulting from the shales. Where earthy limestone originally existed the calcareous constituents become altered to white crystalline marble, while the argillaceous material crystallizes as garnet, vesuvianite, scapolite, augite, hornblende, epidote, etc. It is generally accepted that such a recrystallization is brought about by hot solutions or steam escaping from the magma. The original limestone bed and the resultant marble generally show the same chemical composition. In many cases however an accretion of material took place, this accretion being generally in the form of heavy-metal compounds; where these were deposited in sufficient amount ore-deposits resulted, such being known as contact-metamorphic deposits. It must again be pointed out that the expression 'contact-deposit' is unfortunately even to-day applied a good deal to occurrences having nothing to do with contact phenomena, but which by chance occur along the plane where two rocks come in contact. This wrong use of the term should in all reason be avoided.

Finally, it may also be the case that within the contact-zone an ore-deposit exists which was already present from the beginning and which, in common with the country-rock, suffered subsequently all the alteration imposed by contact-metamorphism. In such cases it is at times difficult to distinguish between an occurrence of pure contact-metamorphic character and another which, present from the beginning, has only had its character obscured in the subsequent turmoil.

(*b*) *Pressure-metamorphism.*—At those places of the earth's crust where in consequence of a horizontal pressure an intense compression and plication of the originally horizontal beds took place, the rocks are often profoundly altered. In many cases this alteration has proceeded so far that the rock resembles the oldest crystalline schists, though distorted fossils present may indicate that the beds are younger and really of Palæozoic or Mesozoic age. Such a complete recrystallization of the original material of the rock has been brought about by pressure and the heat thereby produced, which being conveyed to the weak solutions held within the rock or circulating within its fissures, has given these a greater power of solution. Were any deposit pre-existent within this rock complex, this must also have become altered, and in a manner dependent upon its original nature. Were it a bed of siderite, an alteration to magnetite or hæmatite would be most likely. In considering the genesis of deposits under such circumstances, the re-formation must be distinguished from the original formation. The re-formation of minerals resulting from pressure-metamorphism may be distinguished from that occurring in the contact-zone by the different minerals present as well as by the structure, though where both classes of metamorphism were active at nearly or at exactly the same time these distinctions lose much of their force.

More recently it has been endeavoured to explain the alteration resulting from pressure, upon physico-chemical lines. We refer to *Die kristallinen Schiefer* by U. Grubenmann, and to several works by F. Becke.

(*c*) *Metasomatic Alteration.*—Minerals formed in this manner, like those arising from contact-metamorphism, result from the action of solutions upon already existing minerals. In this process of alteration one minute particle after another of the old mineral goes into solution, this solution then reacting with that containing the germ of the exchange in such a manner that a new mineral of different chemical composition becomes deposited. For instance, if a solution of ferrous carbonate act upon calcite, the change of the latter to siderite proceeds by its gradual passage into solution from which it precipitates solution ferrous carbonate. Becquerel as early as 1852, proved that calcite precipitated lead carbonate from a lead nitrate solution, this same reaction when a longer time was taken, resulting in crystalline cerussite. Similarly, smithsonite would result from a zinc solution; malachite and azurite from a copper solution; siderite and rhodochrosite from a solution containing both iron and manganese, if air were excluded. Sorby also produced siderite by treating calcite with a solution of ferrous chloride. The processes however by which masses of slate and diabase are altered to iron ore, and porphyry into manganese ore, are more complex. In the latter case the lode-like manganese deposits on the

north side of the Thüringer Wald exhibit a transformation so complete that only the quartz of the original rock remains unaffected.

Nature works generally with relatively weak solutions acting through long periods of time, so that in the end the result is proportional to the mass of the solution. The law of mass-action asserts itself especially in these processes of metasomatis. If large quantities of a solution of calcium carbonate act upon barium sulphate, this latter becomes changed to barium carbonate; or vice versa, large quantities of calcium sulphate solution gradually change barium carbonate to the sulphate. It was from such an experiment as this, $BaSO_4 + Na_2CO_3 =$ solution, that Guldberg and Waage started out upon their study of mass-action. Such reactions as these established in the laboratory, are often to be observed in nature, for instance the change from barite to witherite and conversely that from witherite to barite. To such metasomatic change limestone and dolomite are more susceptible than all other rocks. From these two rocks, in addition to the case of siderite which has already been mentioned, several heavy-metal sulphides and especially those of lead and zinc may be formed; it is indeed in this manner that many of the known lead-, zinc-, and iron deposits have arisen.

Besides such occurrences in which the ore is almost exclusively formed by metasomatis, other analogous alterations take place to a subordinate extent in the formation of all useful ore-deposits. The occurrences for instance described on p. 141 and ascribed to contact-metamorphism, originate by an alteration of the limestone in a manner closely related to metasomatis. The difference in fact lies only in the source of the solutions, though, in addition, with contact-metamorphism the crystalline form of the original limestone is less often preserved than with metasomatis.

The occurrence of subordinate metasomatic processes may also be substantiated in many lodes. In the tin lodes of Cornwall for instance, crystals of cassiterite are found as pseudomorphs after felspar, which pseudomorphs, though produced by pneumatolytic action, must nevertheless have been formed by a procedure analogous to metasomatis. In the characteristic greisen zone usually found accompanying these lodes when in granite, the newly-formed minerals often maintain the original shape of the constituents of the granite, a result which also must have been effected by a procedure analogous to metasomatis. With propylitization described on p. 134, similar features present themselves. Even in those cases where to the naked eye little alteration of the country-rock along the lode may be noted, the microscope will often show that considerable changes have in reality taken place. Such changes as these which more generally consist in the formation of sericite, chlorite, quartz, etc., are always more or less closely connected with the formation of the ore now found filling the

fissure. It is stated by some American authors that the extent to which these newly-formed minerals occur is characteristic of the different classes of lodes, and a classification based upon the alteration of the country-rock has even been proposed.

(*d*) *Weathering and other Processes of Alteration.*—In many cases it is not necessary that the mineral undergoing change shall in its entirety be brought into solution. Quicksilver-tetrahedrite for instance may apparently be changed into cinnabar by the removal of As_2S_3 or Sb_2S_3, probably by means of alkaline sulphides.

If an alkaline sulphide act upon metallic silver, argentite is formed; pseudomorphs of this latter mineral after the former may even be observed. Similarly, copper may be converted into cuprite, malachite, or azurite. With those noble metals however which are more inert than silver, as for instance gold and platinum, such changes as these do not appear to be known. The native gold found as a secondary deposition from telluride ores has been formed by the removal of the tellurium, which removal has doubtless been caused by atmospheric agencies. The occurrence of native copper in pseudomorphs after cuprite is attributed by Knop to the action of a weak acid which, from the cuprite, Cu_2O, took CuO, leaving the copper as metal. In addition pseudomorphs of copper after azurite occur, and of silver after pyrargyrite, proustite, stephanite, etc.

Sulphide ores are readily changed to sulphates, oxides, hydrates, etc., by mineral solutions of an oxidizing character; or into carbonates by the action of waters containing carbonic acid. Pseudomorphs of limonite after pyrrhotite and pyrite, have been formed in this manner; of lead sulphate and lead carbonate after galena; and when phosphoric or arsenic acid were present, of pyromorphite and mimetite after galena.

This class of mineral formation is characteristic of the oxidation zone of ore-deposits where the formation of oxides and carbonates, through the decomposition effected by the oxygen- and carbonate-containing water of the atmosphere, may be observed on a large scale. The decomposition of chalcopyrite, $CuFeS_2$, is particularly interesting. Usually limonite is formed while the copper content largely becomes carbonate or oxide, both the copper as well as the iron then remaining *in situ* after decomposition. Where the copper is completely removed, the iron, in the form of limonite, remains alone. More rarely however chalcopyrite may decompose to covellite which remains, while the iron content in that case becomes removed. Equally rare is the formation of copper silicates, such alterations as these depending upon more complicated reactions. Bismuthinite and bismuth by weathering change to bismite; stibnite to valentinite and senarmontite; cobaltite generally to erythrite; the sulph-arsenides of nickel to annabergite, etc.

Sometimes a reduction of the oxides even to metal has taken place. Thus, as mentioned above, pseudomorphs of native copper after cuprite may occur. By the action of gases or solutions specularite may become reduced to magnetite, a reduction which at a somewhat raised temperature requires but little of the reducing agent. This latter change is exemplified at Grängesberg, where along the dykes of pegmatite-granite the specularite has been altered to magnetite.

More frequent however than reduction is the advance of an oxide to a higher state of oxidation, or the transformation of oxides to hydrates or carbonates. Pseudomorphs of hæmatite after maguetite are quite frequent; hæmatite often changes to limonite, cuprite to azurite. With two or more carbonates of one metal distinguished by differences in the amount of water they contain, weathering may produce pseudomorphs of these carbonates after one another, thus malachite after azurite, and azurite after malachite.

Hydrates and carbonates often surrender their water or carbon dioxide. Hæmatite has in this way often been formed out of limonite and out of siderite. In Siegerland it has been observed that the pseudomorphs of hæmatite after siderite exhibit the same volume as the original material, which could only be possible when the solutions effecting the oxidation introduced an amount of iron at the same time. Pseudomorphs of pyrolusite and psilomelane after rhodochrosite are also known.

In special cases, as for instance in the Rocky Mountains and at Broken Hill, silver ores are changed to chloride, iodide, or bromide. While the formation of the chloride in view of the frequency of sodium chloride in atmospheric water is not remarkable, the associated occurrences of the iodide and bromide are more striking. Such alteration in many cases is referred to the action of sea-water or of mother-liquors, and probably rightly so in view of the fact that the two-thousand-year-old slags of Laurion in Greece now, as the result of the action of sea-water, present the formation of laurionite, PbClOH.

The change of smithsonite to hemimorphite and that of copper ores to chrysocolla is fairly frequent.

In addition to all the processes of mineral formation which have been mentioned there are others which have either not been studied at all, or only studied superficially. In this connection investigation at very high temperatures such as have till now only been reached in the electric furnace, is particularly lacking, though experiments made under such conditions would doubtless reveal many new facts. Similarly, mineral formation under great pressure such as must obtain when crystallization takes place in fissures at great depths, has likewise received little attention.

It must here be remarked that one of the chief results of the investiga-

tion of mineral-synthesis is, that one and the same mineral may be formed in very different ways. Many sulphide ores may arise by differentiation from molten silicate magmas, by pneumatolysis, by the reaction of gases and vapours upon one another, or finally by precipitation from aqueous solution. The production of a mineral by a certain chemical process does not therefore justify the statement that this mineral in nature has always been formed in that particular manner. In the investigation of the formation of ore-deposits therefore, the chemical-mineralogical point of view alone is not determinative, but in order to decide the manner in which in each case a particular mineral was presumably formed it is necessary also to consider all the geological factors.

THE RELATIVE DISTRIBUTION OF THE ELEMENTS

LITERATURE

F. W. Clarke. 'The Relative Abundance of the Chemical Elements,' U.S. Geol. Survey, Bull. 78, 1891; 148, 1897; 228, 1904; and 330, 1908.—J. H. L. Vogt. 'Über die relative Verbreitung der Elemente, besonders der Schwermetalle, und über die Konzentration des ursprünglich fein verteilten Metallgehalts zu Erzlagerstätten,' Zeit. f. prakt. Geol., 1898.

The earth's mass consists of:

1. The gaseous envelope, or the Atmosphere.
2. The liquid envelope, or the Hydrosphere.
3. The solid crust, or the Lithosphere.
4. The interior, the Pyrosphere or the Barysphere.

Estimates of the average thickness of the crust have been made by comparing the rise of temperature in depth with the rise in the melting-points of the minerals under pressure. The results thus obtained vary between 40 and 150 km. Vogt in his most recent work [1] estimates between 60 and 80 km.

According to the view generally accepted, both pressure and temperature gradually increase towards the centre of the earth. The conclusion may consequently be drawn that in the interior the critical temperature of all compounds, by reason of intense heat, will long be passed, though, according to Arrhenius, on account of the tremendous pressure the material there present will exist in an extremely viscous condition which he describes as that of gases compressed to be as rigid as iron.

The average specific gravity of the entire earth is about 5·6, while that of the solid crust is only 2·7 or 2·8. It is therefore justifiable to consider that the specific gravity of the interior must be something more than 5·6. This high figure it is sought to explain by assuming the heavy metals, more particularly in metallic condition, to be collected there, an assumption which is supported by Gouy-Chaperon's law, according to which the heavy components of a solution tend to sink to the bottom. Meteorites in their

[1] *Tscherm. Min. Petrogr. Mitt.*, 1907.

composition also lend some support to this view in that these bodies, which must be regarded as fragments of shattered heavenly bodies, consist largely of native iron and nickel.

This assumption—together with the demonstration by French investigators about 1850 that many ores might be formed by pneumatolytic reactions such as that expressed by the formula $SnFl_4 + 2H_2O = SnO_2 + 4HFl$—led to the hypothesis that the heavy metals of ore-deposits were in great part and more or less directly derived from the earth's interior. Later however this hypothesis was abandoned by almost all the authorities when it became recognized that ore-deposits by differentiation could be formed directly from eruptive magmas; by leaching processes, the so-called lateral secretion in the widest sense of the term; and by deposition from mineral-bearing solutions. But be the far original source of the ores where it may, all observations point to the conclusion that the more proximate source is chiefly in the lithosphere and the magmas found therein, and subordinately in the hydrosphere and atmosphere. The composition of these three envelopes has therefore a great bearing upon the derivation of the components of ore-deposits.

While the determination of the average composition of the atmosphere and the hydrosphere offers no particular difficulty, in determining that of the crust it must be remembered that speaking generally each younger bed is built up of material derived from others pre-existing. If the building up of a new bed—that for instance of a sandstone at the sea-coast, of a clay at the bottom of a lake, or of a limestone at any coral reef, be observed—it is seen that:

(*a*) The sandstone consists of the regularly arranged detritus derived from the land, in which detritus quartz by reason of its greater capacity of resistance, predominates.

(*b*) The clay consists of the finest material of pre-existing slate beds deposited afresh in the quiet water of a large lake.

(*c*) The limestone consists of chemical compounds derived from older rocks taken by rivers to the sea, where their separation from solution and eventual precipitation were effected by living organisms.

If accordingly each younger rock is formed in this manner from others pre-existing, then the whole sequence of the sedimentary formations must have arisen from rocks still older at their base, namely, the crystalline schists and the eruptive rocks. The eruptive rocks which intrude the sediments will in their turn consist of mineral originally contained in the stores of magma within the earth's crust. The investigation of the average composition of the solid crust may consequently be started from two points.

1. The fundamental crystalline schists.
2. The eruptive rocks.

The chemical composition of the solid crust may be determined fairly accurately—as was first indicated by Clarke in 1891 and confirmed afterwards by Vogt, Harker, Washington, and others—by putting together a large number of analyses either of the eruptive rocks or of the crystalline schists. Different estimates made on these lines have shown in a striking manner that the average of a large number of such analyses obtained in the one way, is approximately the same as that obtained in the other. In consequence of the fact that the different geological formations in greater part no longer lie horizontal but have been raised and later partly destroyed by tectonic processes, beds of the most varied geological age now appear at the surface. So much is this the case that a knowledge of the earth's crust to an average depth of about 16 km. has become possible. Reckoned to this depth, that portion of the earth's mass of which the composition may be determined, consists approximately of :

Atmosphere	0·03 per cent.
Hydrosphere, sea-water	6·60 ,,
Lithosphere, solid rock	93·40 ,,

AVERAGE COMPOSITION OF THE LITHOSPHERE

	Clarke.	Vogt.		Clarke.	Vogt.		Clarke.	Vogt.
O	47·09	47·20	Ti	0·43	0·33	Ni	0·02	0·005
Si	28·23	28·00	H	0·17	0·17	Sr	0·03	0·005
Al	7·99	8·00	C	0·14	0·22	Li	0·01	0·005
Fe	4·46	4·50	P	0·11	0·09	Cl	0·07	0·025–0·04
Ca	3·43	3·50	Mn	0·08	0·075	Fe	0·02	0·025–0·04
Mg	2·46	2·50	S	0·11	0·06	Sn	...	0·0005–0·005
K	2·44	2·50	Ba	0·09	0·03	Br	...	0·0005
Na	2·53	2·50	Cr	0·03	0·01	Co	...	0·0005

In the above table the results of Clarke and Vogt, the former obtained in 1904 and the latter in 1893, are placed side by side so that in respect to the less frequent elements those of Vogt supplement those of Clarke. According to the latter authority, the more extensively occurring minerals take part in the composition of the eruptive rocks in the following approximate percentages by weight :

Felspar	about 59·5
Hornblende and pyroxene	,, 16·8
Quartz	,, 12·0
Biotite	,, 3·8
Titanium minerals	,, 1·5
Apatite	,, 0·6
Total	94·2 per cent.

It is seen that of the entire mass of the earth's complex crust oxygen

forms nearly one-half by weight. It may be expected that going inwards towards the centre this proportion, in consequence of the increased proportion of native metals and probably of metal carbides, will diminish. This element in every stage of the formation of the earth's crust is the most important agent of the chemical-geological processes; compared with it hydrogen and nitrogen play quite unimportant parts.

Among the halogen elements chlorine, as an essential constituent of scapolite, sodalite, chlor-apatite, etc., appears to be more particularly present in basic rocks. The microscopic cubes of common salt seen floating in liquid inclusions in quartz and other minerals, indicate its presence there also. Fluorine on the other hand in fluor-apatite, in many micas, hornblende, tourmaline, topaz, etc., is an element characteristic of the acid rocks. In spite of the relatively small extent to which the halogen elements occur in the earth's crust, on account of their energy they have played a highly important part in many chemical-geological processes, such for instance as the formation of the tin and the apatite lodes, etc.

The greater portion of the chlorine now known is found in sea-water. The salt beds formed from the oceans of former geological times contain but a fraction of the total amount in the earth's crust. If all the known salt beds were spread out as a covering of uniform thickness enveloping the whole earth, that thickness would at the most not be more than 5 m. which, in proportion to an average thickness of 16 km., would indicate that the chlorine in the salt beds only amounts to 0·015 per cent of the earth's crust. Sea-water contains 50–200 or on an average about 150 parts of chlorine to one of bromine, and about ten times as much bromine as iodine; it may be assumed that the proportion between these three elements in the solid crust is about the same. In consequence of their small extent, bromine and iodine have in general not been of much importance in the formation of ore-deposits; indeed we know of only one instance, and that in lodes on the west coast of South America, where combinations of these elements with heavy metals have assumed any importance.

Sulphur, the average amount of which in the rocks Clarke determined to be 0·11 per cent, is found in the eruptive rocks chiefly in the form of sulphide ores, such as pyrite, etc. Such sulphides, as indicated on p. 129, are soluble to a certain extent in molten silicates, this solubility rising with the temperature and with the basicity of the molten mass. From this it follows that the basic eruptive rocks as a rule contain more sulphur than those which are acid. The presence of sulphurous vapours in volcanic exhalations is well known. Sulphur is the chief factor in the formation of deposits of sulphide ores and of such sulphates as selenite, anhydrite, barite, etc. Selenium, which chemically is closely related to sulphur, accompanies that element in nearly all its deposits,

being consequently found almost regularly in the lead chambers of sulphuric acid works. In amount however it falls far behind sulphur, the relation between the two being as 1 to 100,000, and it is only therefore in exceptional cases that it plays any important part in ore-deposits. Mention must however be made of its occurrence in gold-silver lodes in New Zealand, Sumatra, and Nevada. Tellurium, though in relation to its chemical properties approaches less closely to sulphur than does selenium, nevertheless sometimes occurs in considerable amount with sulphide ores, as for instance in the gold lodes of Western Australia, Colorado, and Siebenbürgen.

Phosphorus, the amount of which in the eruptive rocks has been determined by Clarke to be 0·6 per cent, occurs chiefly in the mineral apatite, which mineral is found in the basic eruptive rocks, excepting labradorite and peridotite. Boron is found chiefly in tourmaline, axinite, datolite, etc., and in acid eruptive rocks. It is only in but few cases that this element occurs in sufficient amount to form useful deposits, though this is so at Sasso in Tuscany and at Volcano, one of the Lipari Islands. In some volcanic exhalations, especially in connection with granitic eruptives, it has however played a not unimportant part.

Silicon after oxygen is the most plentiful element in the earth's crust. The 28·2 per cent of silicon given on a previous page is practically equivalent to 60 per cent SiO_2. A revised estimate based not only upon bulk analyses but also upon considerations of the relative distribution of the different eruptive rocks, on account of the great extent of granite, would probably give somewhat more than 60 per cent of SiO_2. Among the silicates the felspars are the most frequent, and among these the plagioclase felspars are quantitatively more important than the orthoclase.

Titanium occurs particularly in ilmenite, titanomagnetite, rutile, etc., and in certain varieties of pyroxene, hornblende, mica, etc.; it is found chiefly in basic rocks. Zirconium is found chiefly in the mineral zircon which occurs most frequently in nepheline- and augite-syenites and in other intermediate rocks. Zircon also occurs in acid rocks, but only rarely in those which are basic. Germanium was discovered in 1886 by Winkler in argyrodite, and its presence was afterwards established in Bolivian tin ores, and in different niobates and tantalates; it belongs to the rare elements.

Concerning the occurrence of the noble earths, the investigations of Iddings and Cross in 1885, of Derby in 1891, and of Cleve, have afforded information. These elements, more particularly since their employment in the manufacture of gas-mantles, have been the subject of closer study, one result of which has been to show that some of them are not so rare as they were formerly thought to be. Thus allanite, monazite, and xenotime are found fairly frequently in the acid igneous rocks and

in certain gneisses. Before reflecting upon the chances of eventually working such a primary source of monazite it should be realized that the monazite amounts to only about 0·01 per cent, and the average amounts of the other noble earths are considerably less. Cerium and yttrium, which appear to be the most extensive of these, do not probably amount to more than 0·001 per cent and thorium to not more than 0·0001 per cent, after which follow lanthanum, didymium, and thorium. At present monazite is won entirely from gravel-deposits.

Carbon occurs chiefly in the atmosphere as carbon dioxide, but also in the solid crust as carbonates, hydrocarbons, and coal. So various is its occurrence that any figures of its amount are unreliable.

Sodium and potassium are approximately equally distributed. They occur chiefly in the felspars and are therefore found in greatest amount in the acid and intermediate eruptive rocks. Lithium by spectroscopic analysis may be detected in most rocks, though it occurs more frequently in the acid eruptives and in some minerals associated with tin lodes in granite. Of the rarer light metals, rubidium is found in sea-water in quantities one-thousand times less than sodium, and cæsium in still smaller amount.

Calcium occurs chiefly in anorthite felspar, in augite and hornblende, in calcite, and in numerous other minerals, and preferably in basic rocks. Numerous experiments by Dieulafait 1851 ; Breithaupt 1866 ; Sandberger 1858, 1877, 1882, 1885 ; Clarke and Hillebrand 1894 ; and later by Högbom 1895 ; Stelzner 1896 ; and Delkeskamp 1902, have shown that barium is found in many rocks, especially those which are felspathic, in amounts which can by no means be considered small. Strontium often occurs with barium but in smaller amount. Both elements are in greater part associated with basic rocks rich in felspar. Magnesium occurs principally in augite, hornblende, biotite, olivine, in the spinels, dolomite, magnesite, etc., and chiefly in basic rocks. The most important beryllium mineral is beryll which is generally found with acid rocks.

Aluminium, the most extensively occurring mineral of all, is particularly associated with the felspars. It occurs somewhat more plentifully in the basic than in the acid rocks.

Iron occupies the fourth place upon the list of elements given on p. 149, though among the heavy metals it is the first. The different estimates of the iron content of rocks made by Clarke were 5·46 in 1891, 4·71 in 1897, 4·64 in 1900, and 4·46 in 1904 ; by Harker 5·6 ; and by Washington 5·42; so that the average may be put at about 4·5 per cent. Corresponding estimates for manganese by Clarke in the same years as above were respectively 0·07, 0·08, 0·07, and 0·084 per cent ; and according to Vogt as the result of 553 analyses, 0·070–0·086 per cent. Both elements occur

most plentifully in basic rocks, manganese chiefly in silicates; iron however occurs also to a considerable extent in oxide and sulphide ores. While these sulphide ores particularly favour the basic eruptive rocks giving those rocks their high content in iron, the acid rocks have relatively a higher manganese content.[1] The average relation of manganese to iron for all rocks is approximately 1Mn : 40–70Fe, a proportion which also represents very well the relation between the present yearly production of these two metals.

Nickel occurs principally in two forms, firstly in small amounts in some ferro-magnesium silicates and especially olivine; and secondly in pyrrhotite, pyrite, and in the sulph-arsenide ores. Peridotite and its decomposition product serpentine, contain generally from 0·075 to 0·15 per cent of nickel; while diabase, gabbro, and basalt, contain about 0·03 per cent. Nickel in crystallizing from basic magmas associates itself partly with the sulphides and partly with the silicates; among the latter the association is particularly with olivine, and less with the other ferro-magnesium silicates. Thus olivine from an occurrence of saxonite at Riddle in Oregon, according to Foullon contained 0·25 per cent of nickel, while bronzite from the same rock contained 0·04 per cent. According to Stelzner, 0·07 per cent and 0·028 per cent have also been found in the mica of granite and gneiss from Saxony. Pyrrhotite from the gneiss and schists of the crystalline schists generally contains from 0·25 to 0·5 per cent of nickel, while that from the gabbro generally contains a considerably higher percentage. Clarke in 1904 from 243 analyses, found an average of 0·023 per cent of nickel for all rocks, which is probably too high since many rocks, and especially the acid rocks which are practically free from nickel, were not adequately represented in those analyses. The estimate of Vogt made in 1898 was 0·005 per cent which however, contrary to that of Clarke, appears too low.

Cobalt is constantly associated with nickel in olivine as well as in sulphides although it occurs much more sparingly. The nickel-pyrrhotite segregations in gabbro generally contain ten to twenty times as much nickel as cobalt. A collection of 75 analyses of terrestrial as well as meteoric nickel-iron showed the relation of nickel to cobalt in them to be 8–20 : 1. Since a similar result is obtained from analyses of olivine, this figure may be accepted as a satisfactory average.

Chromium occurs mostly in peridotite and in serpentine its decomposition product, these rocks usually containing 0·05–0·50 per cent. Other basic rocks contain at most only 0·04 per cent, while the acid rocks contain still less. Vanadium, as demonstrated by Hillebrand in 1898[2] and later particularly by Clarke, cannot be considered as belonging to the rare elements. It is found principally as the oxide V_2O_5,

[1] Vogt, *Zeit. f. prakt. Geol.*, 1906. [2] *Amer. Journ. of Sc.*

especially in augite, hornblende, mica, and in the iron minerals found in eruptive rocks. Niobium and tantalum, molybdenum and uranium, are all rare metals, and all, with the exception of molybdenum, are found associated with granitic rocks. Radium must be considered as belonging to the very rarest of metals; it occurs most in uranium ores but occasionally also in monazite and thorite.

Tin has been found by Rose, Sandberger, Scharizer, Schröder, Schulze, and Stelzner, in the primary constituents of granite and especially in the mica, up to and beyond 0·10 per cent of SnO_2. Clean orthoclase and plagioclase from the Erzgebirge which Stelzner caused to be carefully analysed, gave tin in amount from a trace to 0·083 per cent of SnO_2. In eleven samples of granite from Banka and Billiton, Winkler found from 0·01 to 0·07 per cent of SnO_2. Tin is in fact very definitely a granitic element. Tin oxide has also occasionally been known to occur in small amount in hornblende from Greenland, in tourmaline, erdmannite, polydymite, pyrochlore, and tritomite, etc. The occurrence of a small amount of its oxide in erdmannite, polydymite, etc., from the nepheline- and augite-syenites of southern Norway, shows that it may also be contained in intermediate rocks; that this is also the case with the basic rocks follows from the demonstration of its existence as traces in the titaniferous-iron ore of basic segregations in gabbro.

The remaining heavy metals zinc, lead, arsenic, antimony, copper, quicksilver, silver, gold, and the platinum metals, etc., are all sparingly distributed, and yet so widely that most of them as for instance zinc, lead, arsenic, copper, silver, and even gold and platinum, may be detected in sea-water. The presence of gold in sea-water has been more than once definitely determined. Sonnstandt in 1872 gave the amount as less than 65 mg. per ton; Münster in 1891 gave 20 mg. silver and 5 mg. gold; Liversidge [1] 30–60 mg. gold; and the very careful analysis of Don [2] 4·2 to 4·6 mg. gold. If an average of 5 mg. be taken and 1200 million cubic kilometres be accepted as the latest estimate of the volume of sea, the total amount of gold in the sea-water becomes 6000 million tons. Since the present yearly production is about 600 tons, this gold if it were exploitable, which is not the case, would suffice for the work of ten million years.

In rock-salt also, including the sylvite and carnallite of the salt beds, Liversidge succeeded in finding 60–120 mg. of gold per ton,[3] and Professor Friedrich in more recent experiments [4] 12 mg. per ton. The associated anhydrite and saliferous clay are also somewhat auriferous; from 60 samples tested, 6 gave gold in weighable quantities. In spite of the comparatively concentrated amount in which gold is found in these

[1] *Journ. Soc. N.S.W.* XXIX. 1895.
[2] *Amer. Inst. Min. Eng.*, 1898.
[3] *Trans. Chem. Soc.*, 1897.
[4] *Metallurgie*, 1906.

salt beds, the actual amount yet remains so small that no profitable exploitation can be imagined. In the mother-liquors of salt lakes amounts up to 1536 mg. per ton have been determined. The silver content of the sea-water is usually several times that of the gold.

The constant presence of the heavy metals in all eruptive rocks, though in small amount—a view long known to have been held by Durocher, Malaguti, Dieulafait, Forchhammer, Bischoff, Sandberger, and others—may be inferred from the fact that not only such metals as copper, arsenic, etc., but even gold, silver, and the platinum metals, occur in some magmatic segregations. The Canadian and Scandinavian nickel-pyrrhotite segregations in gabbro for instance show a constant though minimal content of precious metals. According to Vogt [1] the following relations obtain in these deposits, 100,000 parts nickel to 20 parts silver, $\frac{2}{3}$ part platinum, and $\frac{1}{6}$ part gold. If it be considered that the nickel content in the original gabbro magma amounted to 0·05 per cent, and that the precious metals during magmatic segregation became concentrated in the same proportion as the nickel, then the original gabbro magma contained 0·00001 per cent silver, 0·0000001 per cent gold, and 0·0000004 per cent platinum. Further with regard to platinum, the native occurrence of this metal in magmatic segregations in peridotite, indicates an original platinum content in the peridotite magma.

Copper is also present in the above-mentioned nickel-pyrrhotite deposits but not to the same extent as nickel, the relation between the two being generally as 1 of copper to 2 of nickel. Since copper on account of its intimate relationship with sulphur probably becomes more concentrated in the processes of magmatic differentiation than the nickel, the original copper content of the gabbro magma was probably less than that of the nickel.

From a study of the proportions in which the different metals occur in ore-deposits, conclusions in many cases may be drawn concerning their relative proportions in the rocks. Thus copper and lead may well occur 100 but not 5000 times as plentifully distributed in the rocks as silver; and silver again 100 to 500 times more plentifully than gold. Zinc can be taken to occur at least 100 times and probably 1000 times more plentifully than cadmium.

The occurrence of traces and of minute though still weighable amounts of metals in the rocks, has long been the subject of research and discussion, no agreement of opinion having been reached as to the nature of the association in which the metals thus occurred. The following observations have considerable bearing upon this question. When crystallizing from an eruptive magma, potassium and sodium possessing the greatest affinity for

[1] *Zeit. f. prakt. Geol.*, 1902.

oxygen go entirely, and calcium, magnesium, and aluminium, in greater part, to form silicates. The manganese present is mainly taken up in the ferro-magnesium or in the ferro-magnesium-calcium silicates, while only a small portion passes over to the oxide ores. The chromium of the basic portion of the magma is found partly with the silicates and partly with the important oxide products, chromite and chrome-spinel. Iron, possessing a lower affinity for oxygen than chromium, passes either into the ferro-magnesium and ferro-magnesium-calcium silicates, or into oxide ores, in which latter condition a considerable portion of the original iron content is generally found ; or it passes into sulphide ores and especially into pyrite and pyrrhotite ; or quite exceptionally it remains as metal.

Zinc, which in its bearing towards oxygen lies between chromium, manganese, and iron, occurs in greater part in such silicates as willemite, hemimorphite, the triclinic pyroxenes, and other minerals ; though it is also found in sulphides and in oxide ores. Cobalt and nickel, possessing a lower affinity for oxygen than iron, associate themselves either with the ferro-magnesium and the ferro-magnesium-calcium silicates as in olivine ; or with the sulphides, the nickel more particularly with pyrrhotite and the cobalt more frequently with pyrite ; or exceptionally they occur in the metallic state as in nickel-iron. Tin as oxide associates itself chiefly with the silicates, and again, though less often, with the titanium and zircon minerals. Tin oxide however, when it is contained in greater amount in the magma, may also crystallize as cassiterite. Lead and copper are the last metals in the sequence of affinity for oxygen to form silicates. Lead forms the extremely rare minerals barysilite, ganomalite, etc., and various artificial lead minerals, while copper forms the hydrous minerals dioptase and chrysocolla. Both metals have in addition been found to occur in minute quantities with other silicate minerals ; lead for instance with hemimorphite and some manganese silicates, and copper in blue vesuvianite. The greatest part of the lead and copper is however not found with silicates, but as sulphide compounds, chiefly galena and chalcopyrite. Since apatite is isomorphous with pyromorphite and mimetite, it is always possible that a small portion of the lead may associate itself with apatite ; this has indeed been established by Schertel and Stelzner. With mercury, silver, gold, and the platinum metals, which in their affinity for oxygen are at the bottom of the sequence of metals, it may be accepted that no silicates are formed, but that the fractional amounts of these metals contained in the original magma exist in sulphides, tellurides, and arsenides, though gold and platinum to a smaller extent may also be in native form.

That the rarer heavy metals are distributed so extensively in many

rocks even though the amount be small, has an important bearing upon the 'lateral-secretion theory.' Sandberger [1] and other zealous followers of this theory held the view that the ferro-magnesium and the ferro-magnesium-calcium silicates—mica particularly, but also augite, hornblende, etc.—contained in general small quantities not only of manganese, chromium, zinc, cobalt, nickel, and tin, but also of lead, copper, antimony, bismuth, and even silver. This assertion in regard to the last-named minerals appears however not to have been justified; it was found that the mica, etc., analysed by Sandberger, contained small amounts of sulphide ores filling cracks and crevices. The mica stated by Sandberger to contain silver was shown by the careful research of Stelzner to be free from that metal.[2] Later, in 1898, Don, in New Zealand, by numerous analyses demonstrated that the small amounts of gold which could generally be found in the rocks in the neighbourhood of auriferous deposits were proportional to the amounts of pyrite they contained, so that the gold actually was associated not with the original rock but with the secondary pyrite.

The following figures expressing approximately the relative abundance of the various elements will be of interest. 500 oxygen : 1 sulphur; 10,000–100,000 sulphur : 1 selenium; 500 sodium : 480 potassium : 1 lithium : $\frac{1}{2}$ rubidium; 5 chlorine : 1 fluorine; 2 chlorine : 1 fluorine, in the solid crust; 150 chlorine : 1 bromine : $\frac{1}{10}$ iodine; 400 calcium : 1 barium : $\frac{1}{3}$ strontium; 500 magnesium : 1 beryllium; 1000 aluminium : 1 barium; 10,000 aluminium : 1 cerium : 1 yttrium; 65 silicon : 1 titanium; 25 titanium : 1 zirconium; 25,000 silicon : 1 tin; 60 iron : 1 manganese; 300 iron : 1 chromium; 500 iron : 1 nickel; 10–15 nickel : 1 cobalt; 500–2000 lead or copper : 1 silver; 25–100 silver : 1 gold; 500–1000 zinc : 1 cadmium.

The preference which some elements appear to have for acid eruptives and others for basic, is an important point in the investigation of the genesis of ore-deposits. According to Vogt [3] the following generalizations may be made:

Elements occurring more extensively in Acid Eruptives.—Silicon, naturally most decidedly; the alkali-metals, especially potassium and lithium; beryllium, somewhat; boron, cerium, yttrium; tin, thorium, almost exclusively; zirconium, tantalum, niobium; fluorine, markedly; wolfram and uranium decidedly; molybdenum apparently.

Elements occurring more extensively in Basic Eruptives.—The alkaline earths, calcium decidedly, barium and strontium less so; magnesium strongly; aluminium not very decidedly; titanium decidedly; phosphorus and vanadium decidedly; sulphur markedly; chlorine some-

[1] *Untersuchungen über Erzgänge*, I. 1882, II. 1885; and numerous other treatises.
[2] Kolbeck, *Jahrb. f. B. u. H. W. Sachsens*, 1887. [3] *Zeit. f. prakt. Geol.*, 1898.

what; chromium decidedly; iron, manganese, and more decidedly nickel and cobalt; the platinum metals.

Taking the heavy metals by themselves, tin, wolfram, uranium, tantalum, niobium, and probably also molybdenum, occur more frequently in the acid rocks; while iron, manganese, nickel, cobalt, chromium, and platinum, occur more generally in basic rocks, the two last particularly in peridotite. Zinc, lead, arsenic, antimony, bismuth, copper, quicksilver, silver, and gold, have also been considered by several authors to occur more frequently with the basic rocks. It was thought that this conclusion might be drawn from the fact that many deposits of these metals are connected more or less directly with basic eruptives. Further investigation has however shown that they also occur quite often with acid rocks and accordingly no decided preference for one or the other can on the present evidence be stated to exist; or at least no regular rule formulating such a preference can be drafted.

NATURAL ASSOCIATIONS OF THE ELEMENTS, WITH ESPECIAL REFERENCE TO THE METALS

LITERATURE

Particularly Vogt, Zeit. f. prakt. Geol., 1898.

Most deposits are distinguished by the occurrence together of two or more closely-related elements in amounts more or less considerable. Such natural associations follow in most cases from the fact that these particular elements have many chemical properties in common and that therefore throughout the various reactions which have determined the different stages of concentration from the original occurrence to the resulting deposit, they have found their way together or have not been completely separated. Further, other elements far removed from one another in relation to their chemical properties may eventually be found associated because they make together those chemical compounds which Nature seeks to form in her methods of concentration; thus tin and fluorine in tin fluoride, iron and titanium in ilmenite, gold and tellurium, and the different metals of the sulpho-salts. Against this however it is occasionally found that two elements closely related to one another become separated because of a property the possession of which is not common to both, with the result that at one stage or another during the formation of the deposits a separation of the two was effected. With the garnierite and asbolane deposits for instance, nickel and cobalt have in this manner become so separated that the veins of garnierite occur almost free from cobalt, and the cobalt in the asbolane deposits is practically free from nickel.

When two closely related metals undergo the different processes culminating in the formation of ore-deposits, it is generally the case that one or the other becomes more strongly concentrated and the proportion between the two consequently changes, so that sometimes the amount of one of the metals present will exceed the ratio which it bore to the other in the original rock or magma. When however the proportion between two chemically closely-related metals remains practically the same in a number of deposits of quite different genesis, this proportion must approximately agree with that of the same metals in their original rock or magma. That

this theoretical conclusion is justified in fact is proved by the constancy, mentioned below, of the relation of iron to manganese when these two metals occur together.

The most typical natural associations of metals or elements are found where the metals concerned are closely related to one another, as with nickel and cobalt; zinc and cadmium; gallium and indium; iron and manganese; copper and silver; lead and silver; silver and gold; the different platinum metals; the cerium and yttrium metals; arsenic and antimony; wolfram and arsenic; niobium and tantalum; tin and germanium; calcium, strontium, and barium; chlorine, bromine, and iodine; sulphur and selenium, etc. Of these, nickel and cobalt belong to the same group in the periodic system, and this is also the case with zinc and cadmium; copper, silver, and gold; the platinum metals; the cerium metals; arsenic, antimony, and bismuth; wolfram and uranium; niobium and tantalum; tin and germanium; calcium, strontium, and barium; chlorine, bromine, and iodine; sulphur and selenium. Iron, atomic weight 56, and manganese, atomic weight 55, are also fairly close to one another in that system, but lead and silver are farther apart.

Although iron and manganese are not so closely related as for instance nickel and cobalt, or zinc and cadmium, they nevertheless invariably accompany one another in ore-deposits, though their quantitative relation varies. The magmatic deposits of titaniferous-iron in basic eruptive rocks contain on an average 150 times as much iron as manganese, while the apatite-iron deposits formed equally by magmatic differentiation though in acid igneous rocks, carry from 500 to 1000 times as much iron as manganese. From this, on theoretical grounds, it is justifiable to draw the conclusion that in such magmatic deposits the iron of the original magma is generally more strongly concentrated than the manganese.

The contact iron deposits, such as those at Elba, in the Banat, and at Christiania, are distinguished by a low manganese content and the same is also the case with the pyrite deposits, such as those at Rio Tinto, Röros, Fahlun, etc. With both these classes of deposit the proportion of iron to manganese generally varies between 500 and 1000 : 1. Among the Scandinavian deposits which are apparently bedded in the old crystalline schists, the lean ores of Striberg and Norberg, consisting of quartz and specularite, carry on an average about 400 times more iron than manganese. With the ferruginous mica-schists of Norway, which were probably formed by hydrothermal processes, the proportion is 250 : 1, while with ordinary magnetite ores it is between 20 and 100 : 1. Among the Palæozoic hæmatite, limonite, and siderite deposits, which in general have been formed by hydrothermal processes that is either by sedimentation, metasomatis, or precipitation in lodes, the hæmatite, as far as the lodes are concerned, is distinguished

by having a lower manganese content than the other two. For instance with the ore of Cumberland and Lancashire the relation of iron to manganese is as 500 : 1 ; it may indeed be said that in greater part it contains but traces of manganese. Limonite on the other hand possesses a manganese content which though variable is usually high, and sometimes so high that all gradations between manganiferous iron and ferruginous manganese, are represented. Siderite has usually a high manganese content, the relation of the iron to manganese varying from 100 : 1 to 10 : 1, though sometimes the proportion of manganese is still higher. The following examples are representative :

Siderite from Steiermark	23·3 Mn : 1 Fe
Siderite from Siegerland	15·0 Mn : 1 Fe
Siderite from Rostoken, Hungary . . .	26·5 Mn : 1 Fe

Minette has always less than 1 per cent of manganese. Bog iron ore and lake ore present all gradations from iron ore poor in manganese to manganese ore poor in iron.[1] The manganese iron ores from Oberrossbach in Hesse and Lindenermark near Giessen contain the two metals in fairly equal proportions, that is as 1 : 1.

Between deposits of iron and those of manganese there is therefore no sharp line of division ; they pass through all gradations from one to the other, some deposits containing equal amounts of both metals. It follows that not only may the ores at one end be spoken of as iron ores and those at the other as manganese ores, but between the two a third class, that of the iron-manganese ores, must be conceded. The intimate association of the two elements is based upon the many chemical properties which they possess in common, there are indeed but few hydrochemical reactions by which iron and manganese may be separated from one another, a subject further discussed in the chapter dealing with the genesis of bedded iron ores.

The world's production of iron ore in 1906 amounted roughly to 125,000,000 tons, to which total all classes of deposits, sedimentary, metasomatic, precipitated, and magmatic, contributed. From the united total of the outputs of iron and manganese ores

Several million tons presented the relation . . .	1000–750 Fe to 1 Mn
,, ,, ,, . . .	750–500 ,, 1 ,,
,, ,, ,, . . .	500–250 ,, 1 ,,
20 million tons, at least, presented the relation . .	250–100 ,, 1 ,,
50 million tons, perhaps, presented the relation . .	100– 50 ,, 1 ,,
Several million tons presented the relation . . .	50– 25 ,, 1 ,,
,, ,, ,, . . .	25– 10 ,, 1 ,,
,, ,, ,, . . .	10– 1 ,, 1 ,,
Finally, perhaps, one million tons presented the relation .	1– 50 ,, 1 ,,

[1] Vogt, *Zeit. f. prakt. Geol.*, 1906.

From this statement it is seen that the bulk of the ores contain 100 or a little less than 100 of iron to 1 of manganese, a relation which agrees very well with that in the earth's crust, this as determined from many bulk samples being approximately 50–75 to 1.

The world's production of manganese ore, until the last few years during which the amount from India has become so important a factor, depended a good deal upon the production from Tschiatura in the southern Caucasus, from which in normal years about $1\frac{1}{2}$ million tons were obtained. When however these deposits in consequence of disturbance or difficulty of communication did not deliver their usual quantity, very little manganese ore appeared on the market.

As mentioned on p. 153, the nickel-pyrrhotite deposits in gabbro contain nickel and cobalt approximately in the proportion of from 10 to 20 of nickel to 1 of cobalt. A similar proportion is obtained by the examination of meteorites and also by taking the average of a large number of rock analyses. A result substantially different however is presented by the sulphide and arsenide nickel and cobalt ores when these are found together in lodes, as at Bieber, Riechelsdorf, Schweina, Schneeberg, Dobschau, Siegerland, and in Canada. In such cases all gradations are found between nickel ore poor in cobalt on the one hand and cobalt ore poor in nickel on the other. In general also in such occurrences the cobalt content is much higher than with magmatic lodes, from which it would appear justifiable to draw the conclusion that by those hydro-chemical processes which resulted in the formation of these lodes, cobalt became more strongly concentrated than nickel. A similarly greater concentration of cobalt is also found with some bed-like deposits, such for instance as the so-called 'cobalt fahlbands' at Modum in Norway, which carry about 13 times as much cobalt as nickel, and the so-called 'garnet ores' of Querbach and Giehren in Silesia, the working of which Frederick the Great in his time endeavoured to resuscitate.

The only example of the almost complete separation of the two elements is presented by the garnierite and asbolane occurrences of New Caledonia and Frankenstein, where, within decomposing serpentine, garnierite practically free from cobalt appears in veins, while in separate though neighbouring deposits asbolane practically free from nickel has been deposited. The probable cause of this separation is discussed later under the description of the garnierite deposits.

Zinc and cadmium, with gallium and indium, also generally occur associated. Though with sphalerite, the most common zinc ore, the cadmium content may exceptionally rise to 3 per cent, it is not usual to find the proportion higher than 1Cd to 60Zn, and it is generally only about 1 : 600, or roughly 0·1 per cent of the ore. In smithsonite and hemimorphite, probably

because cadmium as a rule passes less readily into aqueous solution than zinc, the cadmium content appears to be very low. At the decomposition of the cadmium-bearing sphalerite of Lüderich, the sulphide of zinc goes readily into solution, while that of cadmium remains as a green covering of the mineral greenockite over the decomposed sphalerite. The amount of cadmium found in rocks, in harmony with that found in zinc ores, generally falls far short of one-hundredth that of the zinc. Gallium and indium, which in the periodic system are closely related to zinc and cadmium respectively, are also found in sphalerite, though only in small amount. An occurrence at Freiberg of that ore, comparatively rich in indium, shows a relation of this metal to zinc as 1 : 1000, while two other occurrences rich in gallium, one from Lüderich and the other from Pierrefitte in the Pyrenees, presented the proportion 1 gallium : 30,000 zinc.

Copper and silver, even as lead and silver, have many chemical properties in common, and are consequently generally found associated in nature. Among the world's deposits of copper those which are remarkable for their low silver content, not only relatively but absolutely, are those of Lake Superior where native copper occurs in melaphyre. This copper is practically free from silver although occasionally and as a mineralogical curiosity crystals of native silver are found occupying the vesicular cavities in the melaphyre. The pyrite deposits also are remarkable for the very small amount of silver they contain ; with those of southern Spain containing from 2·5 to 4 per cent of copper it is usual to find from 25 to 35 grm. of silver per ton, representing a relation of 1000–1200 of Cu to 1 of Ag. With the pyrite exported from Norway the proportion is about the same, while the smelting ore from Röros, Sulitjelma, etc., produces refined copper with an average of from 0·04 to 0·05 per cent of silver, or 2000–2500 of copper to 1 of silver. A similar though somewhat higher silver content is also found in the pyrite of Rammelsberg, Fahlun, Åtvidaberg, etc.

At Butte, Montana, the most important copper district yet known, the copper lodes, excluding the contents of the silver lodes proper, contain on an average 400 of copper to 1 of silver. In Cornwall, Chili, etc., the copper is generally accompanied by some silver, usually from 0·01 to 0·1 per cent. The copper produced from the *Kupferschiefer* of Mansfeld contains a materially higher proportion of silver, the usual content being from 0·55 to 0·60 per cent, or 175 of copper to 1 of silver. The other occurrences of copper shale in Germany, such for instance as those in the Thüringer Wald and at Riechelsdorf, show however that this high silver content is not characteristic of such deposits, the former carrying practically no silver while the latter carries but 40 grm. per ton. Further evidence showing that in general all copper deposits contain some silver has

become disclosed by the more modern processes of copper refining, especially that of electrolysis.

Putting together all the figures expressive of the relation of the amounts of copper and silver to one another there are but few deposits where the silver is less than 5000 : 1 ; perhaps one-quarter of the world's output of copper comes from deposits having the relation 5000–2500 of Cu to 1 of Ag ; another quarter 2500–1000 : 1 ; a third 1000–500 : 1 ; several important deposits 500–250 : 1 ; while finally there are a few deposits where the relation is 250–100 of copper to 1 of silver. With still higher amounts of silver present, copper ores pass step by step to silver ores, though with these in most cases the actual amount of copper present is several times that of the silver. Deposits such as those of Kongsberg and St. Andreasberg where the silver occurs with practically no copper, are infrequent. All those occurrences where the silver proportion is extremely low, such as those of Lake Superior, have originated by chemical-geological processes, which in their action concentrate copper to a greater extent than they do silver.

The reason that lead and silver so frequently occur together lies in their similar behaviour in many chemical reactions. It is seldom that a deposit of lead ore occurs in which the relation of the silver to lead is less than 1 : 10,000, equivalent to 0·01 per cent in ordinary lead. Most deposits contain 1 : 5000, but often the amount of silver is still higher. Throughout the Freiberg district for instance it is about 1 : 150 ; in the silver lodes of St. Andreasberg it is again much higher ; while at Kongsberg the amount of silver is actually more than that of the lead. In general therefore it may be said of the relation of the amounts of lead and silver that, as was also the case with copper and silver, the lead ores gradually pass over and become ores of silver.

Silver and gold are almost invariably found together in the same deposit, though the relation of their amounts varies extremely. Among the gold-silver-lead and silver-lead deposits the following classes are generally distinguished : the old silver-lead lodes ; the old gold-quartz lodes ; and the young gold-silver lodes. With the first, that is the old silver-lead lodes such as those at Kongsberg, Freiberg, and Clausthal, the amount of gold contained is very small though the relation between gold and silver is not usually lower than 1 : 10,000. This relation may in fact be taken as an average for the whole Kongsberg district, in which however some lodes have as low a relation as 1 : 20,000. For the Freiberg district it may be reckoned to be from 1 : 5000 to 1 : 10,000 ; for the Harz, Przibram, and the Rhineland, it may again be put somewhat higher. In particular cases, as at Svenningdal in northern Norway, these old silver lodes may contain so high a relation as 1 of gold to 500 of silver.

With the old gold-quartz lodes the amount of gold present is usually more than that of the silver, and the relation may even be as high as 10 of gold : 1 of silver. With the young gold-silver lodes on the other hand this relation is reversed and the amount of silver is almost always substantially the greater. For instance at Siebenbürgen all gradations are found from 1 : 1 to 1 : 10 of gold to silver ; at Schemnitz and Nagybanya the relation is much more variable, ranging from 1 : 1 to 1 : 150, gold to silver. At the Comstock Lode it is 1 of gold to 24 of silver, while at Cripple Creek, exceptionally, it is 10 of gold to 1 of silver.

These two noble metals are not only found together in their own particular deposits, but also in others of varied origin, and especially in copper deposits. The reason of this probably lies in the fact that copper, gold, and silver, belonging to the same group in the periodic system, exhibit certain similarities in their chemical relations. The pyrite deposits have generally a small percentage of copper, a small silver content, and a still smaller but nevertheless always present amount of gold. When considering the occurrence of silver, it was seen that the pyrite from southern Spain contains from 25 to 35 grm. of this metal per ton; the amount of gold is only from one-twenty-fifth to one-hundredth of that amount. Similar proportions occur with the Norwegian pyrite occurrences. Bessemer copper from Sulitjelma contains 0·0448 per cent of silver and 0·0004 per cent of gold, which is roughly equivalent to a relation of 100 of silver to 1 of gold. The deposits at Röros and at Meraker show similar proportions. At Fahlun the amount of gold is considerably higher, the ordinary copper ore there containing 2·81 per cent of copper, 18·1 grm. of silver, and 3·3 grm. of gold per ton, or approximately five times as much silver as gold, while in addition selenium is also found. With the copper lodes in granite at Butte, Montana, the relation is 125–200 of silver to 1 of gold, a relation which is approximated by several other similar occurrences. The small noble-metal content with the nickel-pyrrhotite deposits in gabbro is especially interesting ; in Canadian ores this substantially consists of gold and silver in the proportion of 1 Au : 25–50 Ag.

Even with those deposits in which it is evident that the silver has been considerably enriched it is not often that the amount of gold falls lower than 1 : 10,000, while it is sometimes as high as 1 : 1000. The proportion of gold in the original rock would naturally have been higher.

The metals of the platinum group nearly always occur together in nature. Native platinum is therefore accompanied in many of its deposits by iridium and osmium ; more rarely by palladium and the other members of the group. It has already been stated on p. 155, that platinum

occurs to some extent in the nickel-pyrrhotite deposits ; in this occurrence also it is accompanied by the other metals of its group. Among these it is not only the platinum which possesses economic importance but, since the discovery of the osmium lamp, osmium also.

Platinum and its associates appear as segregations in eruptive rocks and, as mentioned above, also as constituents of the nickel-pyrrhotite segregations which have similarly separated from eruptive magmas. Beyond this however they are practically absent from all those deposits which have been formed by precipitation from solution, that is to say, from the lodes of the other metals, though exceptionally the occurrence of traces of platinum in some gold-, silver-, and copper lodes has been observed. This absence may be ascribed to the extreme chemical inertness of platinum, which metal with most reagents is much more difficult of solution than gold. That is however not to say that the average platinum content of the crust must be less than that of gold.

Arsenic and antimony accompany one another very often though they may be separated by many specific reactions, in which fact the possibility is presented that in many deposits they may occur separated. Bismuth belongs to the same periodic group though in its chemical properties it differs materially in some points from the two elements just mentioned. The most important point of difference is that under ordinary conditions it forms no soluble sulpho-salt with the alkaline sulphides, this being probably the reason that it does not occur so often in lodes with arsenic and antimony as might have been expected.

Wolfram and uranium accompany one another in many deposits closely associated with granite magmas, an observation which applies also to niobium and tantalum. The relation between tin and germanium is discussed later when describing the silver-tin lodes of Bolivia. Mention of the cerium and yttrium metals has already been made on p. 152.

Of the three elements belonging to the sulphur group—sulphur, atomic weight 32; selenium, 79; and tellurium, 127 — selenium is more closely allied with sulphur than with tellurium. In consequence tellurium is more often found to occur alone and to be characteristic of certain particular occurrences, whereas selenium almost always accompanies sulphur even though its amount may be minute. There is evidence of this in the fact already stated that selenium is almost always found in the lead-chambers of sulphuric acid works. Selenium deposits are therefore identical with those of sulphur, these being : (*a*) native sulphur in volcanic districts ; (*b*) sulphide lodes as at Lehrbach, Zorge, and Tilkerode in the Harz, etc. ; (*c*) copper shales ; (*d*) pyrite deposits as at Fahlun, Rio Tinto, Rammelsberg, etc. In most of these deposits the relation between the amounts of sulphur and selenium is from 10,000 to 100,000 : 1.

Although tellurium tends to occur in separate deposits and apart from the other two elements, it is nevertheless often found with selenium in the telluride lodes of the young gold-silver group. Chemical analysis has shown that tellurium may in such cases be replaced to the extent of 1·5 per cent of its amount by selenium.[1] Investigation of the gold-silver deposits of Sumatra has shown that selenium may also occur in deposits specially characterized by its presence. The nature of its association in such cases has not yet been satisfactorily determined, since the fineness and completeness with which it is distributed within the quartz of those lodes has made it hitherto impossible to obtain any clear idea of the occurrence. It is however certain that no tellurium is present and it is presumed therefore that the gold occurs exclusively in combination with selenium.

Besides the association of closely related elements in deposits of very different genesis, another regular association of chemically estranged elements is found in some occurrences. Titanium and iron for instance occur together in titaniferous-iron segregations in eruptive rocks. While it was formerly accepted that the occurrence of titanium in iron ore was limited to such segregations, more recent investigation has shown that this statement only applies to titanium in large amount. Smaller amounts may occur in iron ore which has been formed exclusively by thermo-chemical processes. Just as titanium is an almost constant associate of bauxite formed by metasomatis from limestone, so also do the metasomatic iron ores and precipitated beds of iron ore contain a small amount of titanium. The association of iron and titanium deserves attention, because when the latter exceeds a certain percentage, smelting becomes more and more difficult with increase in the amount of titanium present. Ores containing up to 2 per cent of TiO_2 are without question accepted by smelting works, but from 2 to 4 per cent, penalty deductions are made. Vanadium and iron are not only found together in magmatic deposits of titaniferous-iron ore but also in many deposits of iron which have been formed by hydro-chemical processes. The explanation of this is probably that vanadium oxide like iron oxide is precipitated by alkali from an aqueous solution. Vanadium and titanium occur together in the titaniferous-iron deposits of magmatic origin on the one hand and in the rutile of the pneumatolytic apatite lodes on the other.

The association of tin and copper in certain tin-copper deposits is an interesting occurrence. Such deposits are found both in Cornwall as well as in the celebrated tin deposits of the Herberton district, Australia, where one known as the Lancelot has latterly excited considerable interest. It is possible in the case of such deposits to demonstrate that the tin lodes are

[1] Krusch, *Zeit. f. prakt. Geol.*, 1903.

actually separate from those carrying the copper. In others again where there are changes in the country-rock such as might have influenced the deposition, the two lodes may occupy different stretches of the same fissure. In addition to the two metals named, a good many others such as bismuth for instance may also occur, rendering the subsequent dressing of the ore much more difficult.

The association of tin and silver is especially pronounced in the tin deposits of Bolivia, first more comprehensively described by Stelzner. Although in this occurrence tin and silver often occur together they nevertheless, as the recent investigation of Steinmann has shown, also occur apart and in separate deposits. In the Freiberg district and in that of the argentiferous lead-zinc deposits of Argelèze-Gazost the association of tin and silver in the same deposit is illustrated by the occurrence, close to the surface, of crystals of cassiterite with argentiferous galena.

Zinc and lead form minerals which, times beyond number and in deposits widely different in genesis, are found together. This association is metallurgically deserving of great attention since it has not yet been found possible to successfully recover small percentages of zinc at the same time as lead. When making a valuation of such a deposit, the intergrowth of the two must therefore be closely studied in order to be able to judge of the possibility of separating the two minerals by the various operations of dressing.

Copper, nickel, and cobalt are found together in the nickel-pyrrhotite deposits and in many lodes and pyrite deposits. Copper and manganese are known occurring together in great quantity in the oxidation zone of the important copper deposits of Arizona, and in gold lodes at Boleo in Lower California. Neither silver and manganese nor gold and manganese are associated to the same extent; the two former however are found together in the silver lodes of Butte, Montana; the two latter at Verespatak and Nagyag in Siebenbürgen.

The association of cobalt and manganese deserves more attention. A substantial portion of the cobalt ore coming from New Caledonia is marketed in the form of asbolane, an oxidized mixture of manganese-, iron-, and cobalt minerals. The occurrence of these two metals, cobalt and manganese, together may perhaps be explained by the fact that both are precipitated from a neutral solution by oxidation. Manganese is also occasionally a substantial constituent of smaltite, the ore in this case being known as manganiferous cobalt ore, in distinction to that which is free from manganese and which being amenable to more simple processes of extraction may be treated considerably more cheaply.

Barium and manganese are found together in many deposits. In the manganese lodes at Ilmenau on the north border of the Thüringer

Wald, and at Ilfeld on the south side of the Harz, it is the rule for barium also to occur. With the metasomatic iron-manganese deposits the original barium content of the limestone is sometimes found concentrated in crystals of barite intimately interwoven with the iron and manganese.

Silver, bismuth, and cobalt make a characteristic combination of metals in the lodes at Schneeberg. The recently discovered smaltite lodes in the Coleman district of Canada carry masses of silver so large that the silver content may reach as much as 25 per cent of the ore. The nature of this occurrence is however such as to suggest that it is an enriched silver zone near the surface. The association of silver and cobalt has this significance, that no process is as yet known by which both metals may be recovered together without considerable loss of the silver.

Gold and tellurium occur together in the so-called telluride lodes of the young gold-silver group, in which the tellurium content may sometimes be considerable. It is characteristic of such occurrences that only a portion of the gold appears to be combined with the tellurium; the other portion, which is occasionally the larger, being associated with pyrite.

Quicksilver and silver or quicksilver and gold comparatively seldom occur together in such proportion that the ore is primarily a quicksilver ore. Quicksilver in consequence of its physical properties occupies a unique position and this is also the case with its ores. On the other hand its occurrence in small amounts in silver-gold lodes is quite frequent, especially with the telluride lodes. There can be no doubt that in these cases the mineral solutions from which these deposits were formed contained mercury, gold, and silver, at the same time, and that deposition resulted from processes capable of bringing about the precipitation of all those metals.

Chromium occupies a similarly isolated position which, seeing that the mineral is so widely distributed, is somewhat striking. It is found principally in the chromite magmatic deposits, though it also occurs to a very small extent in titaniferous-iron ore. In almost all other deposits it is entirely wanting.

Tin also occupies an exceptional position in relation to the ore-deposits, in that, although many other metals may occur in tin lodes, tin itself is comparatively rare in deposits of other metals. It has been found in isolated cases in the uppermost portion of lodes which carried mainly lead-, silver-, and zinc ores below; occurrences of this sort having been noticed at Freiberg and on the north slope of the Pyrenees.

In some deposits a single metal occurs more or less by itself, an occurrence such as must have resulted from particular processes capable of effecting the precipitation of only one metal or of others only to a small extent. To such as these belong the deposit of silver ore at Kongsberg in

which the chief minerals are native silver and argentite ; the quicksilver deposits as at Almaden, where practically only cinnabar occurs ; the copper deposits at Lake Superior which in the primary zone contain the copper almost entirely as metal ; and the lodes of garnierite in decomposed serpentine at New Caledonia, and at Frankenstein in Silesia.

From this description of the natural associations of the different metals it may be said that three groups of deposits may be differentiated : the first, and by far the largest, that in which the metals present are closely related to one another ; the second, considerably smaller, in which the metals present, while possessing no close chemical relation, are dissolved and precipitated by the same processes as those to which the deposit as a whole owes its existence ; and a third and smaller group which includes those occurrences where a single metal is found more or less isolated, either because it occupies a chemically isolated position or because the particular deposit has resulted from those processes which the particular metal because of properties which it possesses in common with no other alone has survived.

THE ORIGIN OF ORE-DEPOSITS

The elucidation of the processes whereby metals become concentrated to valuable ore-deposits, in other words the interpretation of their genesis, forms the most difficult but at the same time the most interesting part of the study of ore-deposits.

In the case of many deposits which in relation to their geological position, form, and content, have been closely investigated, no agreement has yet been reached concerning the features of the processes to which they owe their existence. For instance not many years ago four different theories were advanced to account for the formation of the celebrated iron deposits at Gellivare, Kiirunavaara, and Svappavaara in Lapland, namely, precipitation, metasomatis, pneumatolysis, and magmatic differentiation. The dispute concerning the origin of the pyrite deposits, which were formerly placed in a group by themselves, has already continued for more than half a century without a settlement acceptable to all having been reached. The animated discussion between Stelzner and Sandberger relative to the application of the 'lateral secretion' theory to the elucidation of the formation of the lodes in the Harz, the Erzgebirge, and at Przibram is still fresh in the memory. On the other hand it must be said that present knowledge is such an advance upon that previously available that with many deposits it has been possible to follow step by step all the stages of concentration from the attenuated distribution within the original rock to the finished ore-deposit; and with others to recognize the greater portion at least of the processes which resulted in their formation.

The consolidation of the previously existing molten magma to form the first solid crust must be regarded as the point from which the metals commenced to separate, or at least as one of the most important of the earliest stages in that separation. Investigation has shown that the specific gravity of this crust is from 2·7 to 2·8, while that of the earth as a whole is 5·6. A difference so large as this between the average specific gravity of the known rocks and that of the whole earth may only be explained by the assumption that the heavier materials,

in consequence of a magmatic differentiation, concentrated themselves in the earth's interior, leaving in the solid crust but a small amount available for subsequent concentration into ore-deposits. It follows that this first magmatic differentiation, in so far as the solid crust is concerned, did not advance the concentration of the metals, but on the contrary withdrew them.

With further differentiation however within the mass of the silicate magma some metals segregated themselves more particularly in the basic rocks, others in the acid, while a large number varied their association with one class of rock or with the other, according to circumstance. Considering only those elements which are of substantial importance towards the understanding of the genesis of ore-deposits, iron, manganese, nickel, cobalt, chromium, the platinum metals, titanium, phosphorus, sulphur, and chlorine may be regarded as basic elements; uranium, tantalum, niobium, wolfram, zinc, thorium, boron, fluorine, and silicon may equally be regarded as acidic; while the other important metals, gold, silver, copper, and lead, cannot as yet be said to have established any preference for one class of rock or the other. It is natural therefore that some of the useful deposits show the same tendency as their dominant metals to occur in connection with acid rocks; that others show the same preference for basic rocks; while others again show no decided preference.

Useful deposits are not formed by all the processes of mineral formation which have already been enumerated. Of these only the following enter the question of the genesis of ore-deposits:

1. Crystallization from the molten condition.
2. Pneumatolysis.
3. Contact-metamorphism.
4. Metasomatis.
5. Precipitation from solution:
   (*a*) in lodes, etc.
   (*b*) in beds on the surface, sedimentation.
6. Mechanical concentration.

1. Formation of Ore-Deposits by Crystallization from Molten Matter

Within the material of a natural complex of rocks which have consolidated from the molten condition, the metallic elements present are by no means uniformly distributed, but generally show a preference for certain basic or certain acid members. Pyrrhotite for instance is found chiefly in norites and but little in other basic rocks. This preference for a particular

basic or acidic rock constitutes the second stage in the formation of ore-deposits.

If the distribution of any particular metal in these rocks be investigated it is found that while it may occur as an accessory constituent throughout, only in specially suitable places is it found as an enrichment pronounced enough to be an objective in mining. Nevertheless magnetite, ilmenite, chromite, pyrrhotite, pyrite, and chalcopyrite, particularly, are found concentrated in this manner. The average chromium content of the entire crust is given by Vogt as 0·01 per cent Cr. This by magmatic differentiation becomes concentrated to 0·2 per cent in peridotite, and finally to 40–60 per cent Cr_2O_3 in the magmatic deposits of chromite illustrated in Fig. 141. Such deposits are termed magmatic segregations. According to their composition oxide, sulphide, and metallic magmatic segregations may be differentiated. With reference to the importance of deposits arising from magmatic differentiation, it is to be remarked that chromite is exclusively found in deposits formed in this manner, though in no case do these reach any size. Similarly the known titaniferous-iron deposits, illustrated in Figs. 1, 2, 15, and 143, are exclusively of magmatic origin. The other iron- or apatite-iron deposits occurring in eruptive rocks, such as those at Kiirunavaara, at Gellivare, and in the Lofoten Islands, are also according to recent investigation rightly to be regarded as the products of magmatic differentiation. Although generally the deposits of this group are small there are some among them which are immense, as for instance those at Kiirunavaara and Routivare. Other deposits of exclusively eruptive origin are the nickel-pyrrhotite occurrences, illustrated in Figs. 14 and 142, some of which are of huge dimension. According to the recent investigations of Vogt and Brögger, the Norwegian pyrite deposits at Röros, Sulitjelma, etc., are to be regarded as intrusive deposits of magmatic origin, while according to Weinschenk this in all probability will also hold good for that at Bodenmais in Bavaria.

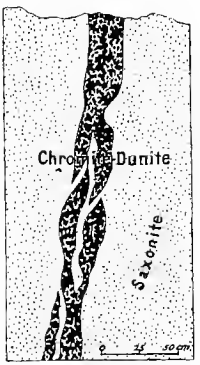

Fig. 141.—Magmatic segregations of chromite in saxonite. Compare with Fig. 13.

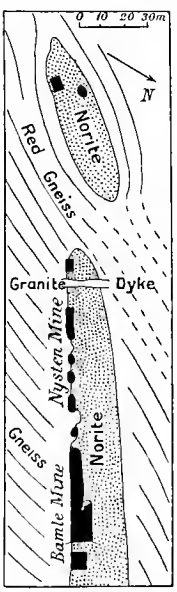

Fig. 142.—Magmatic segregations of nickel-pyrrhotite at the contact of norite with crystalline schists.

Speaking generally it may be said that since the so-called basicity of a rock is to some extent dependent upon the amount

of heavy metallic oxides contained, the basic rocks must be regarded as being more favourable to the formation of such magmatic segregations than the acid; but that since, with these latter, streaks of more basic character are found, it follows that under specially favourable circumstances a considerable portion of the heavy-metal content of an acid eruptive magma may be found concentrated in an ore-deposit.

The manner of formation by differentiation within a magma postu-

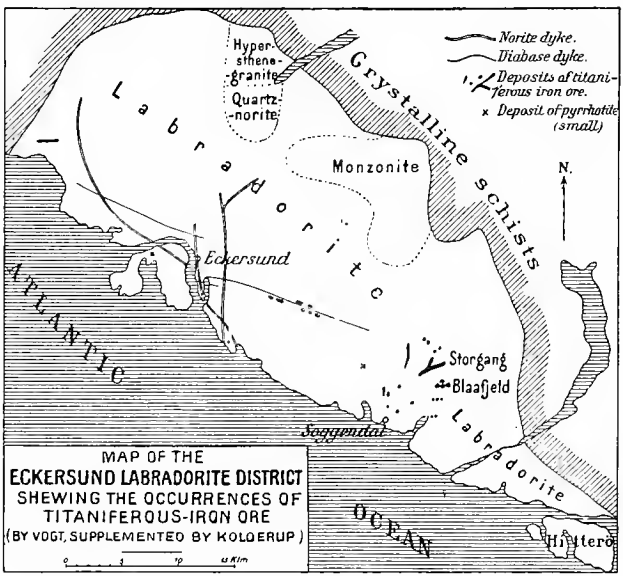

FIG. 143.—Disposition of magmatic segregations in the labradorite district of Ekersund-Soggendal.

lates for these deposits a position within eruptive rocks, or exceptionally in the immediate neighbourhood of such rocks. This disposition is illustrated in Fig. 143. The form of these deposits has already been mentioned on p. 13.

While in the formation of the deposits of this group there be several stages though but one main process, with all other ore-occurrences several processes are operative; that is, after a more or less effective concentration by magmatic differentiation the metal content becomes extracted either in solution or in gaseous form to be deposited afterwards and elsewhere as an ore-deposit. Typical examples of such an origin are afforded by the tin lodes, the apatite lodes, the contact iron ores, the young gold-silver lodes, the Bolivian tin-silver lodes, and the occurrences of quicksilver.

2. The Formation of Ore-Deposits by Pneumatolysis

Pneumatolysis is the sum of those mineral-forming phenomena in which, as described on pp. 132–135, gases and vapours play a part. One entire class of deposit, that of the tin lodes, owes its existence entirely to the action of these gases or vapours either between themselves or upon the rocks with which they come in contact. Since these lodes which are referable to the pneumatolytic effect of a granitic magma, are found in part in the granite itself, it follows that their formation began after the granite magma around its periphery had already consolidated. The fact that tin lodes are not found with every occurrence of granite shows that within the granite itself the tin is variously distributed, more here, less there. If the association of tin with granite be regarded as the first stage in the formation of the deposit, its concentration together with fluorine, etc., at particular places must be regarded as the second. To all appearances, after solidification of the magma had proceeded long enough to form a crust, the tin, in vaporous or gaseous condition, was exhaled from the magma still fluid in depth and introdnced into fissures rent in the solidified crust. From the fact that the minerals usually accompanying tin are characterized by containing fluorine it is probable that in this process of formation that element played a considerable part. As described on pp. 134, 135, concurrently with the deposition of the tin, the granite country-rock becomes greatly altered, this alteration being particularly characterized by the introduction of further silica together with tin and lithium, the whole result being the formation of greisen.

The second stage therefore in the formation of tin lodes is the extraction of such elements as tin, wolfram, etc., from the acid magma, largely with the help of fluorine; while finally the third stage is the deposition of these elements and of quartz in the fissures and in the mass of the country-rock. The conclusions which the miner may draw from this mode of formation are:

1. That as long as exploration work continues in fresh granite showing no sign of greisen there is little immediate chance of striking tin lodes.

2. That as the formation of greisen consists chiefly in an intense silicification of the granite, those portions of that rock which carry tin will resist weathering and erosion, and accordingly will stand out prominently upon the surface.

Seeing that the apatite lodes owe their formation to phenomena which in many ways are analogous to those responsible for tin, it appears proper to consider them here. In the district of Ödegaarden in southern Norway such lodes occur in gabbro, which rock in its original condition according to Vogt contains 0·65 per cent of P_2O_5. In the subsequent concentration

of this material chlorine plays the part which in the case of tin is undertaken by fluorine, and the characteristic minerals of this occurrence therefore contain chlorine. The original hydrochloric acid content of the gabbro, amounting to about 1·4–1·5 per cent, is found concentrated in the two minerals scapolite and apatite; of these the latter is found concentrated in the lodes while the former occurs principally as the characteristic alteration product of the gabbro country-rock, constituting the so-called scapolitization which is just as characteristic of these lodes

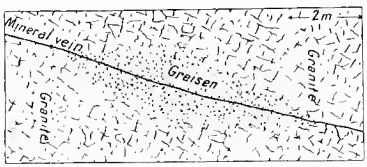

FIG. 144.—Greisen formation along a narrow vein of tin ore. Cornwall.

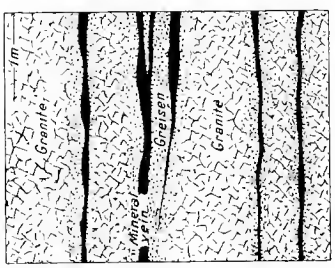

FIG. 145.—Granite altered to greisen along mineral veins. Telemarken, Norway.

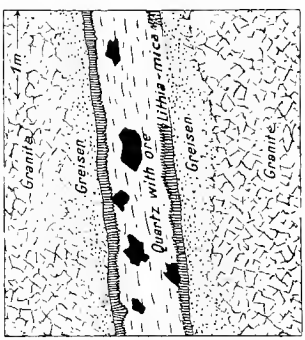

FIG. 146.—Larger vein of tin ore showing crusted structure and the formation of greisen.

as the greisen is in the case of tin. The apatite concerned is the chlor-apatite which differs materially from the fluor-apatite of the tin lodes.

It may be accepted that in this case the hydrochloric acid is the agent which, in a manner analogous to the action of hydrofluoric acid in the case of tin, extracts from the gabbro the mineral constituents of the apatite lodes and carries them to the fissures where they are afterwards deposited. This procedure is described by Vogt as 'acid magmatic extraction.' According to analyses two-thirds of the phosphorus originally distributed throughout the gabbro at Ödegaarden has thus become concentrated in the apatite lodes.

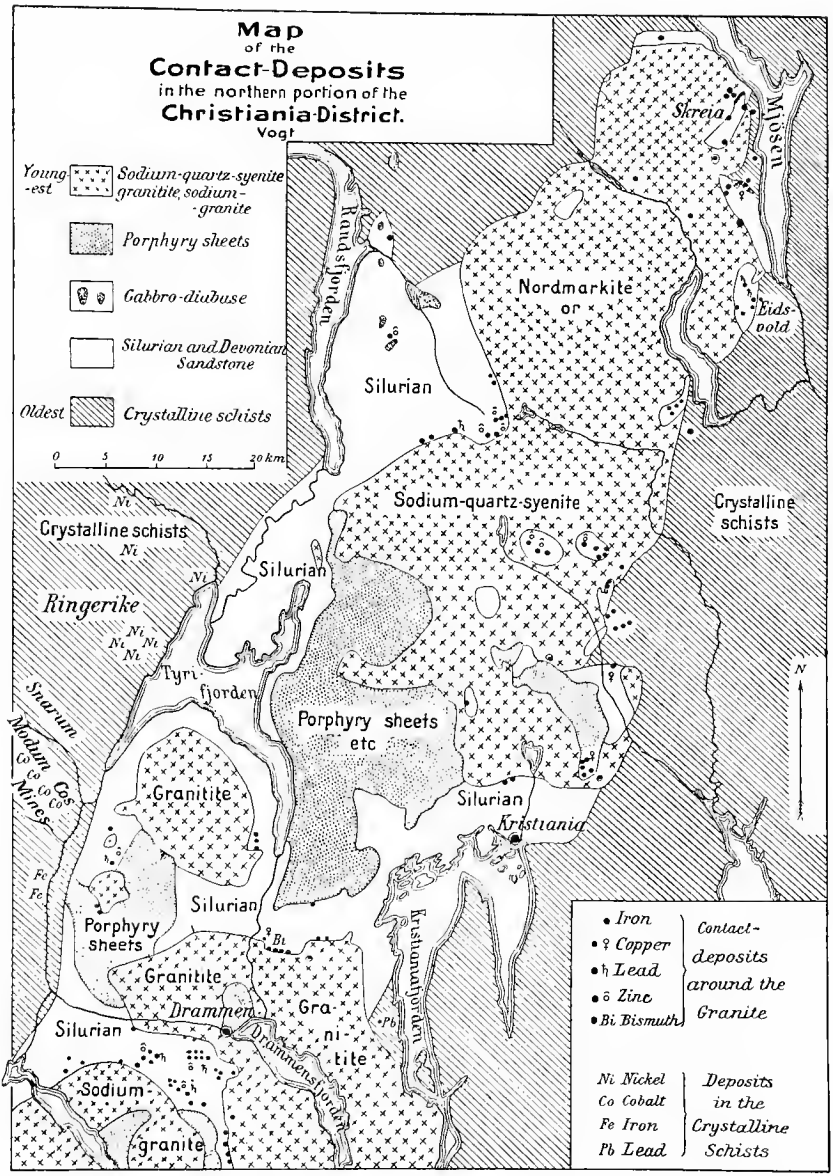

FIG. 147.—Immediate and collateral, oxide and sulphide, contact-metamorphic deposits in the Christiania district.

3. The Formation of Ore-Deposits by Contact-Metamorphism

The nature of contact-metamorphism has already been described in

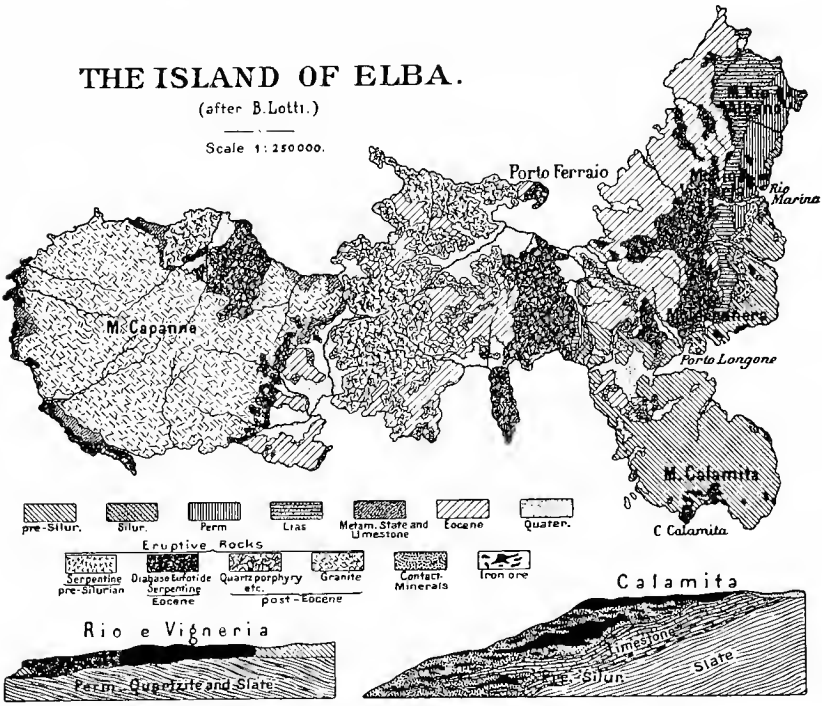

Fig. 148.—The relation between occurrences of granite and porphyry on the one hand and iron deposits on the other, on the island of Elba. In the sections the consequent metasomatic replacement of the limestone into ore is shown.

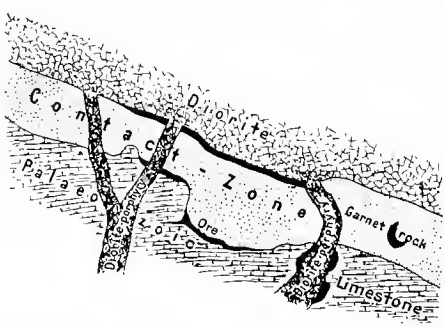

Fig. 149.—Immediate and collateral contact ore-bodies in relation to the position of the eruptive rock. Illustration taken from an occurrence in the northern Urals.

the chapter upon mineral formation. In numerous cases it is accompanied by an accretion of material from the eruptive magma by which accretion deposits of such oxide ores as magnetite, specularite, or of such sulphide ores as pyrite with or without gold, galena, sphalerite, chalcopyrite, etc., have been formed. Deposits of this class are illustrated in Figs. 147–150.

Contact-deposits appear

either immediately at the periphery of an eruptive mass or very close to it, in which latter case they are known as collateral contact-deposits. They

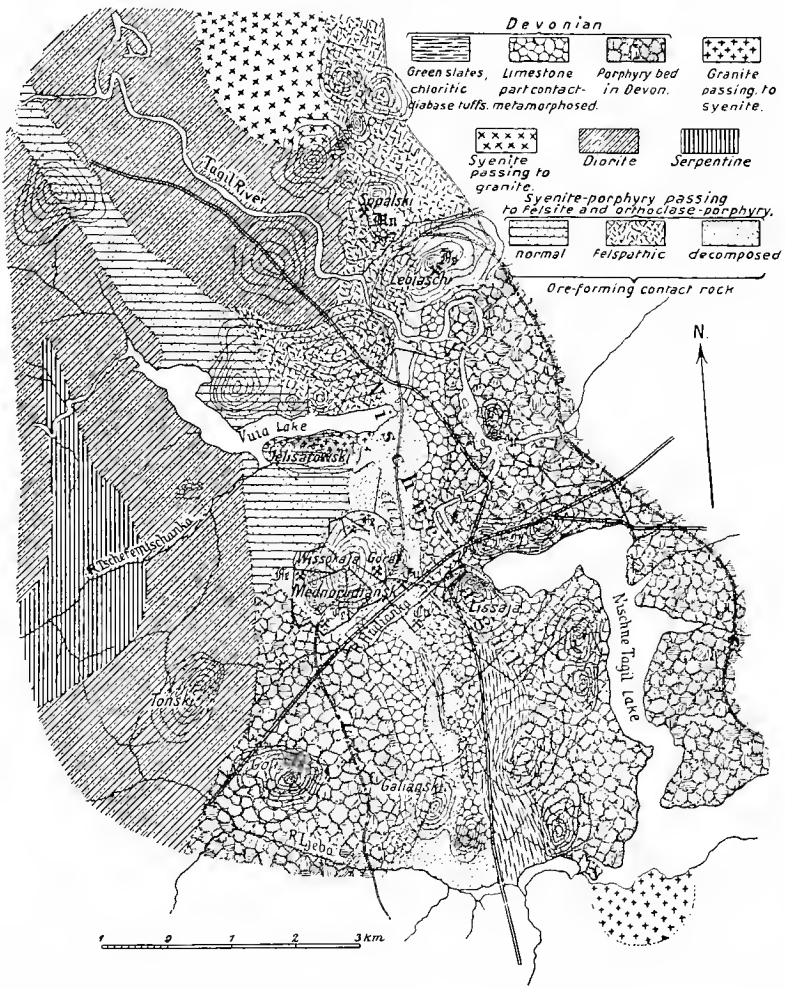

FIG. 150.—Geological position of the contact iron deposits of Wyssokaia Gora, which, contrary to the usual experience with such contact ore, contain an abnormally high phosphorus content. The genesis of these deposits is however disputed.

are not to be found within the eruptive itself but in its contact-zone; the recognition of contact phenomena in the country-rock becomes therefore of great importance in tracing such occurrences.

Contact-deposits, such as those illustrated in Figs. 147–150, are generally

associated with limestone which by contact action becomes in greater part altered to marble but also to a lesser extent to ore-deposits. With these occurrences the appearance of such contact minerals as garnet in the altered limestone and andalusite or chiastolite in the altered slate is characteristic. The contact action is generally more intense the nearer the eruptive rock is approached, while in the immediate neighbourhood of an ore-body it is often particularly intense, to a degree termed by Vogt ' contact super-metamorphism.' [1]

Contact iron ores are generally remarkable in that titanium is either entirely absent or present only to a very small extent, and the amount of manganese they contain is small. On the other hand they often contain considerable amounts of sulphur. With many of these deposits such as those of Elba, the Banat, and Christiania, the phosphorus content is low, though the large occurrences in the Urals, which are for the present regarded as belonging to this group, contain more of this element. The fluorine and boron minerals, fluorite, tourmaline, axinite, etc., characteristic of the occurrences of cassiterite, are entirely wanting in most of these contact-deposits, or when this is not entirely the case the amount present is nevertheless very small.

It is a striking fact that it is the acid intrusives particularly, and especially granite, which exercise this contact action resulting in the formation of iron ore. This naturally also holds good for such acid magmas as are at the same time connected with the deposition of tin. In such cases it is usual to find both classes of deposit, tin and iron, sharply distinct and separate, though occasionally gradations from one to the other are found, as for instance at Schwarzenberg in the Erzgebirge, where contact iron ore predominates and tin ore is subordinate. Such gradations also occur at Pitkäranta in Finland.

Large occurrences of oxide ores belonging to this group are only known in the case of iron. Among sulphide occurrences that of Broken Hill, one of the largest lead-zinc-silver ore-bodies in the world, may be mentioned though its genesis is disputed. The stages in the formation of ore-deposits by contact-metamorphism may be stated to be :

(1) The concentration of heavy metal in particular sections of the solidifying rock, by magmatic differentiation.

(2) The extraction of this metal by solutions exuding from the magma and its transference to the contact-zone.

(3) The deposition of ore within that zone, chiefly by metasomatis, which in such case is spoken of as contact-metasomatis.

[1] '*Potenzierte Kontaktmetamorphose.*'

4. The Formation of Ore-Deposits by Metasomatis

As mentioned in the preceding paragraph the deposition of ore in contact-metamorphic deposits takes place in great part by metasomatis. In addition there exists a whole series of deposits where the deposition, though likewise resulting from metasomatis, has not taken place within any contact-zone nor does the deposit stand in any perceivable relation to eruptive phenomena. Such deposits as these constitute the metasomatic deposits in the narrower sense of the term.

The phenomena of metasomatis, described in the chapter on mineral formation, have produced their greatest effect in the formation of iron- or iron-manganese ores, illustrated in Figs. 59 and 151, and lead-zinc ores,

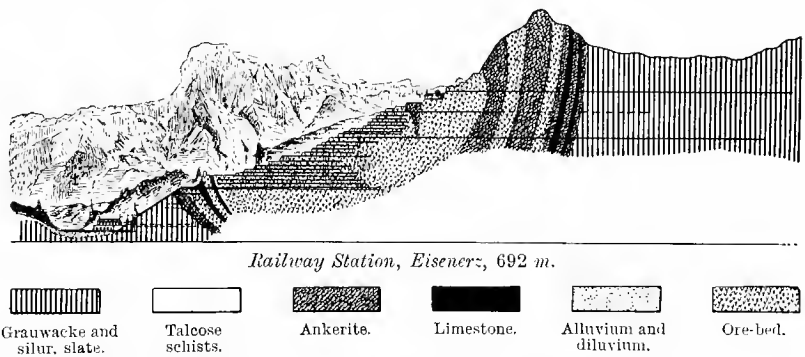

Fig. 151.—Siderite bed formed by metasomatis, and by complete change of the limestone brought to resemble an ordinary sedimentary bed. Erzberg near Eisenerz, Steiermark.

illustrated in Figs. 58, 60, 152, 154, while copper and pyrite deposits have only resulted to a lesser extent. The most important zinc deposits of the world belong to this group, and among the metasomatic iron deposits some are of great importance, as for instance those of Bilbao in Spain and Erzberg in Steiermark.

With these metasomatic deposits only the last stage of their formation is known, that is the alteration of the limestone or the original rock, whatever it might have been, by mineral solutions. The source of these solutions however is not known. The nature of the formation of these deposits postulates that they are usually in close genetic relation with tectonic fissures and lodes.

5. The Formation of Ore-Deposits by Crystallization or Precipitation from Solution

With numerous lodes there is much to suggest that the ascending solutions from which they became filled were in connection, far or near, with molten magma, that in fact these solutions were consequent upon the intrusion of an eruptive mass and represented one of the last stages of the eruptive phenomena.

Careful observations in this connection are available, among others, in regard to the quicksilver deposits and to the young gold-silver lodes. Many of the former stand in close genetic relation to Tertiary or even to Quaternary eruptive masses and to the solfataras which accompany them. At Sulphur Bank in California and at Steamboat Springs in Nevada mineral formation is still proceeding, and the chemical and physical conditions under which the deposition of ore is occurring at those places may be studied almost as though the investigation were being undertaken in the laboratory.

The researches of Christy, Le Conte and Rising, Posepny, Becker, and Melville, show that at the above-mentioned places cinnabar is being precipitated from heated waters wherein it is held in solution by an excess of sodium sulphide, Na_2S. From such a solution precipitation may take place by dilution, by oxidation, by escape of H_2S resulting from the decomposition of Na_2S, by ammonia at a low temperature, or finally by the reducing action of carburetted hydrogen. It is more than likely that many of the other occurrences of cinnabar have resulted from one or other of these reactions. While however so many points are available to explain the precipitation of the cinnabar, none are forthcoming with regard to its source nor to the chemical processes by means of which at the place of its origin it was brought into solution. Becker suggests that the hot springs in California, during their passage through the granite there, have taken up a small amount of quicksilver, but this interpretation would in no wise explain the intimate association of the quicksilver deposits with the young eruptive rocks. Seeing that these deposits, whether in California, at Krain, or the Sierra Morena, etc., always show the same monotonous character, and that, in large amount, the cinnabar is accompanied only by pyrite, it may be accepted with a fair amount of certainty that all these deposits have been formed by analogous processes. Since also in the neighbourhood young eruptive rocks are generally to be found, it is probable that the magma of these rocks stands in causative relation to the origin of the quicksilver.

The young gold-silver lodes such as those at Nagyag, Kremnitz, Schemnitz,

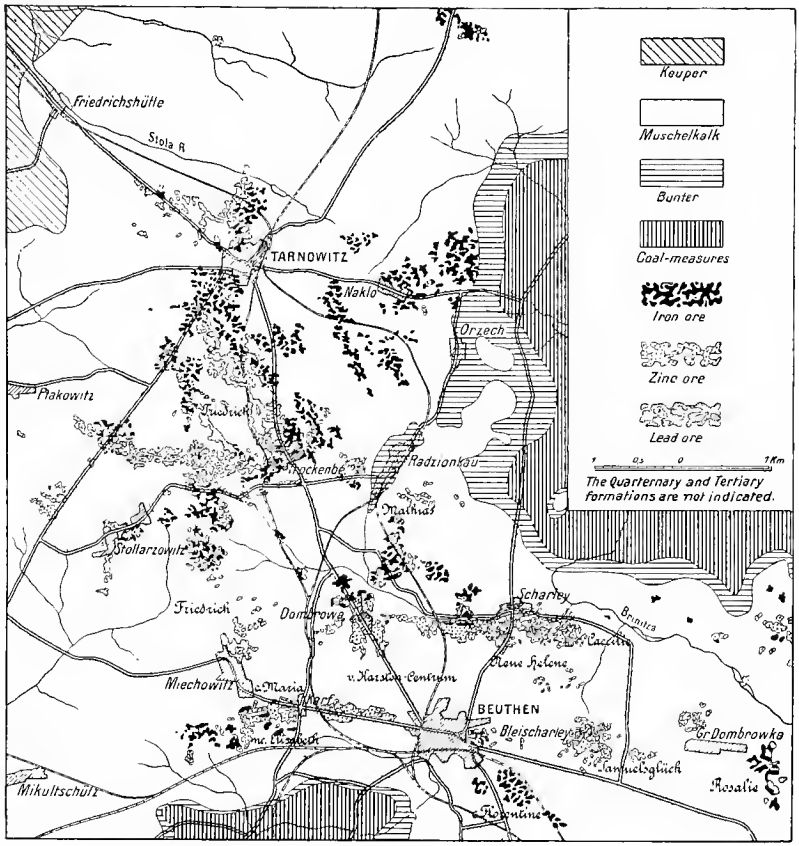

FIG. 152.

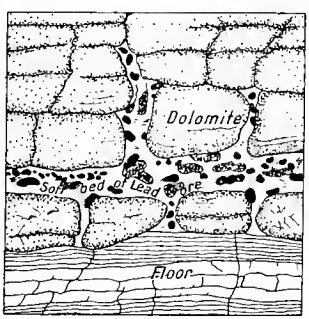

FIG. 153.

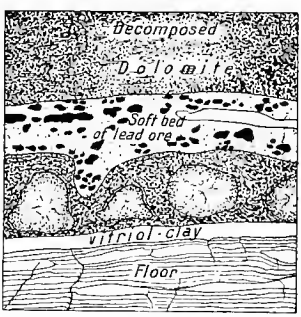

FIG. 154.

FIGS. 152, 153, 154.—Sulphide lead-zinc deposits of the Beuthen and Tornowitz synclines in Upper Silesia, where the limestone first has been altered metasomatically to galena, sphalerite, and pyrite, and later by oxidation to smithsonite and limonite. Fig. 152 is a general plan of the deposits, while in Figs. 153 and 154 special sections are given.

Comstock, etc., to which the tin-silver lodes at Potosi, Oruro, etc., in Bolivia are closely allied, have a wealth of properties in common:

(*a*) These lodes are generally associated with the occurrence of eruptive rocks of Tertiary or late Mesozoic age, though they are in no way regularly dependent upon any one particular rock. Indeed such a complex of eruptive rocks may contain acid, intermediate, and basic members, it being understood that acid rocks contain above 60 per cent of SiO_2, intermediate rocks between 50 and 60 per cent, and basic rocks less than 50 per cent. Leaving out of consideration the exhalations which may still be observed to-day, the formation of the lodes appears to belong to the end or to one of the end phases of the particular vulcanicity.

(*b*) Not only with the gold lodes but also with those carrying silver the most important gangue is quartz. After quartz comes calcite which not infrequently is accompanied by rhodochrosite, and then barite, while fluorite and the other fluorine and chlorine minerals are usually wanting. Exceptionally however fluorite in considerable amount occurs at Cripple Creek. The absence of fluorine and chlorine in the majority of these lodes is remarkable and indicates that these elements in general can have had no material influence upon their formation. While it was formerly accepted that the boron minerals were practically absent, more recent investigation has shown that tourmaline occurs in certain districts, Western Australia for instance, in lodes of this class.

(*c*) In their chemical-mineralogical relations the young gold-silver occurrences are particularly characterized in that gold and silver accompany and replace one another in various proportions. The known occurrences may indeed be so arranged that all gradations from argentiferous gold ores to auriferous silver ores may be presented. The gold bullion won from such deposits cannot be reckoned off-hand as gold, but a determination of its fineness, which may be 500 or less, is necessary.

Some of the lodes of this group are the real source of the metal tellurium, and the association of gold with tellurium has already long been remarked. The intimate manner in which free gold and tellurides are found intergrown in primary ore in Siebenbürgen, in Colorado, and in Western Australia, is evidence that both became formed under exactly the same conditions. It has already been mentioned in the chapter concerning the natural association of metals that tellurium may in part be replaced by selenium. It is further characteristic of the lodes of this group that sulphides often occur in considerable amount, pyrite especially; this indeed is sometimes so much the case that the miners speak of the primary ore not as telluride but as sulphide ore. Galena and sphalerite are less abundant though in Schemnitz they are more plentiful than pyrite. Finally chalcopyrite is often present though in subordinate amount.

With the silver lodes the occurrence of the sulpho-salts, pyrargyrite, proustite, stephanite, tetrahedrite, bournonite, is interesting and characteristic, while in some few places combinations with bismuth are to be noticed.

The tin-silver lodes of Bolivia, on account of their richness in tin, wolfram, and silver, occupy a place by themselves, though on the other hand the frequent occurrence of arsenic, antimony, and bismuth, connects them with the young gold-silver group. If it be remembered that tin forms a sulpho-salt and that the sulphides of tin, antimony, and arsenic, are known to be soluble in an alkaline sulphide, the genetic divergence between the Bolivian lodes and the young gold-silver lodes does not appear great.

(*d*) With these lodes the almost constant alteration of the country-rock to propylite, as mentioned on p. 134, is of particular significance in relation to their genesis. This alteration consists in the formation of chlorite, talc, kaolin, calcite, etc., and in the introduction of pyrite and other sulphides, by the action of mineral solutions upon the normal Tertiary eruptive whereby finally a complete change of that rock is effected. The chemical composition of propylite shows that the solutions circulating in the fissures were in most cases rich in carbon dioxide and in sulphur compounds. Exceptionally also, as at Verespatak, they contain silica causing thereby and at the same time a silicification of the country-rock. Propylitization is just as characteristic of the young gold-silver lodes as the formation of greisen is of those of tin.

(*e*) The young gold-silver lodes in relation to their mineral content approach the quicksilver occurrences. Both are connected with young eruptives, and in both cases quartz is the most important gangue, after which comes calcite, while the fluorine minerals are usually practically absent. In addition, the arsenic and antimony minerals so characteristic of the young gold-silver group are also found to occur in the quicksilver deposits, though in small amount. Finally it may be noted that lodes of both ores are sometimes found together though this is seldom, and even gradations from one to the other may occur though this is quite exceptional.

Opposed to these points of agreement are others of divergence. While with the young gold-silver lodes sulphides and sulpho-salts are often abundant, the quicksilver-deposits are characterized by poverty in such minerals. Further, while in the one case gold and silver became concentrated in the solutions, in the other the presence of quicksilver characterized the solutions.

The question from whence the young gold-silver lodes obtained their noble-metal content is just as unexplained as the source of the quicksilver in its deposits. There can to-day however be no doubt that this

content was not obtained by leaching from the immediate country-rock, that is by lateral secretion in the original sense of that expression. It is equally difficult to explain by the extractive action of heated water upon the various solid rocks through which the solutions passed, that is by lateral secretion in a wider sense. Since the geological complexes of the different districts where such lodes are found always differ and are various, a genesis such as this would not explain the close agreement invariably found between them. It would appear much more natural to accept the dependence of these lodes upon a young eruptive formation to the extent that they derived their material directly from the magma itself.

Such a derivation has also been accepted for the tin and apatite lodes, hydrofluoric acid providing the means of extraction in the first case and hydrochloric acid in the second. With the young gold-silver group, solutions of the sulpho-salts and carbonic acid were the active agents. Where for instance an alkaline sulphide is dissolved in a magma, that magma would be capable of taking up arsenic, antimony, bismuth, tin, gold, silver, quicksilver, on the one side, and tellurium and selenium on the other, from a molten mass. With eruptive magmas of similar composition, the composition of the lodes would also be similar, and the varying proportions between the different metals may therefore, apart from different chemical and physical factors, be ascribed to differences in the composition of the original magma. Other variations in the mineral solutions from which the lodes were formed may also have resulted from the precipitation of certain constituents before the lode fissure was reached. A point of particular importance in the explanation of the occurrence of silver, especially in such lodes where calcite is abundant, is that silver carbonate is even more readily soluble in water containing carbon dioxide than calcite. The precipitation of ore from a sulpho-salt solution can be taken to have proceeded in a manner similar to that now in evidence at the recent quicksilver deposits.

The stages in the formation of the lodes of the young gold-silver group may therefore be set down to be :

1. The concentration of the noble metals in certain sections of an eruptive magma by magmatic differentiation.

2. The extraction of these metals from this magma presumably by sulpho-salt solutions or carbon dioxide.

3. The transference of the same from the magma to the fissures.

4. The precipitation of the minerals in lodes and country-rock.

The individual lodes of the old lead-silver-zinc group in relation to their genesis exhibit much that is common to the group as a whole. A statement of the more important characteristics becomes on this account, and because

the greater number of all known lodes belong to this type, of great importance.

Their mineralogical character varies; all gradations are found from the silver lodes of Kongsberg carrying little else than silver and argentite, to the typical lead-zinc lodes of Clausthal which have but a low silver content. Districts lying so close together as Clausthal and St. Andreasberg, and of which presumably the ores were formed in much the same manner, may show great divergences in their mineralogical character. In the case of St. Andreasberg this may in part at least be ascribed to secondary change, but in the Freiberg district the different

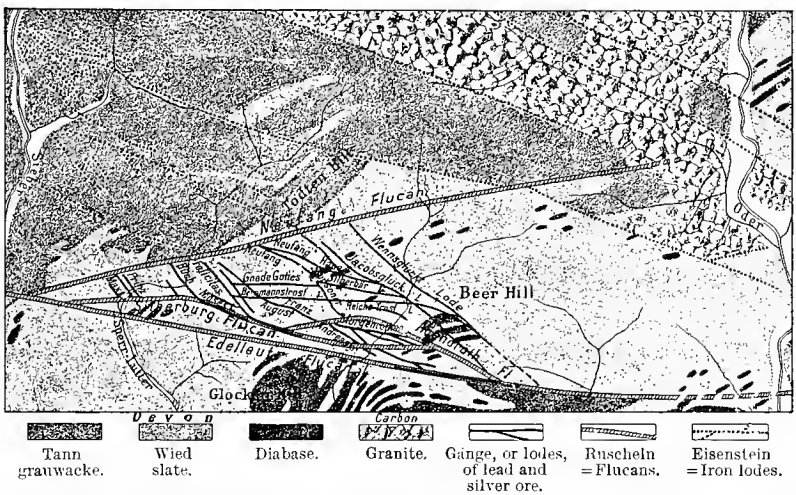

FIG. 155.—The St. Andreasberg district situated in the wedge of country between the Neufang and Edelleute Flucans. In these lodes the silver is principally contained in silver ores proper, while in the Clausthal district not far away it is quite otherwise contained.

lode systems, undoubtedly primary, embrace extreme types belonging to this group.

These old lead-silver-zinc lodes usually contain but little gold. No alteration of the country similar to propylitization may be observed, although metasomatic changes resulting sometimes in the formation of chlorite and sometimes in the deposition of silica, are always present.

If extreme types of the young gold-silver lodes and of the old lead-silver-zinc lodes be compared, very little similarity in their mineralogical character is apparent. The lodes of Schemnitz however which belong to the young group, in their intergrowth of quartz, galena, sphalerite, marcasite, and chalcopyrite, agree strikingly with many of the lodes of the Freiberg and Clausthal districts belonging to the old group. From this it

follows that the old lead-silver-zinc lodes must often have been formed in a manner and by a procedure similar to the young gold-silver lodes, and the difference between the two groups may be described as quantitative rather than qualitative. It agrees very well with this view of their possible genesis that in extensive districts such as those of the Erzgebirge and the Harz a dependence of the lodes upon deep-reaching tectonic dislocations and eruptive phenomena has long been established. The material of these lodes has undoubtedly been brought up from depth, in solutions which probably had a composition similar to that from which the young gold-silver lodes resulted. The source of the metals in these solutions is however even more problematical than with the last-named group.

The old gold-quartz lodes consist chiefly of quartz with auriferous pyrite and free gold. They have therefore to this extent a striking resemblance to some of the lodes of the young gold-silver group, though almost always there is this difference, that the gold of the latter group is accompanied to a large extent by silver while that of the old gold group is comparatively very pure.

With these gold-quartz lodes, the telluride ores rarely occur to any extent, though as mineralogical curiosities they are present in many cases, as for instance in the lodes of Bömmelö in Norway, where tetradymite occurs in minute quantities. The accumulation of telluride minerals remains therefore exclusively an association with the young gold-silver lodes. Selenium is found in many cases in considerable amount, as for instance in the seleniferous galena-bismuthinite deposit at Fahlun, which also contains gold and which Vogt regards as a link between the pyrite deposits and the sulphide gold-quartz lodes. Quartz is the chief gangue mineral; fluorite is generally wanting or occurs only as a mineralogical curiosity. The occurrence of sulpho-salt minerals subordinate to pyrite is sometimes important; bismuthinite for instance characterizes the occurrence of gold ore at Svartdal in Norway.

If the mineral content of these old gold-quartz lodes be taken in many cases to indicate the presence of sulpho-salt solutions having a composition similar to that accepted for the young gold-silver group, the source of such solutions would be a still greater question than with the younger group. In most cases it is not possible to establish any sort of connection with any eruptive rock whatever, and where such is possible the rock is one of Palæozoic or Mesozoic Age.

With these old gold-quartz lodes therefore only disconnected stages in the formation of the deposit are known.

The deposits of native copper at Lake Superior, though possessing in part a lode-like character, differ however from lodes in that they are chiefly shattered zones which have become impregnated along the

fractures produced. The native copper is found in beds chiefly of melaphyre but also of conglomerate and breccia, either filling vesicules, veins, or pockets, or cementing fragments of quartz-porphyry. It is characteristic of these deposits that the copper is closely associated with calcite, chlorite, prehnite, and zeolites. Practically speaking when the oxidation products which have resulted entirely by the activity of the surface waters be left out of consideration, no other ores occur. A similar association of minerals is found under analogous circumstances in basic augite-porphyry at Moss and at Horten in the Christiania district, and again in basalt in the Faroe Islands.

In all these occurrences the native copper appears to be genetically connected with basic eruptive flows or sheets and without question the deposition was by precipitation from solution in which the occurrence of zeolites, chlorite, calcite, etc., indicates that silica and carbon dioxide were present. From the advanced decomposition of the basic country-rock it may also be taken that this must have played a material part in the mineral formation. It might be thought that this precipitation of native copper from solution might well have happened by electrolysis, but it is probable that the reduction was effected by minerals containing ferrous oxide, such as magnetite, augite, etc. The occurrence of kernels of magnetite within metallic copper and the fact that generally much ferric oxide occurs in these deposits may be regarded as evidence of this. Concerning the source of the copper solution no reliable data are available. The view that these deposits resulted from lateral secretion concomitantly with the zeolitization of the eruptive sheet requires further proof.

With these deposits of native copper, likewise, only disconnected stages of the mineral formation are known.

Concerning the Direction of the Source from whence the Mineral Solutions came.

With lodes this may be very varied, necessitating therefore a more exhaustive discussion. The historical development of this question will not be considered here as this is done fully in the chapter upon lodes. There are three views held, these being known respectively as the descension, ascension, and lateral secretion theories.

(*a*) The descension theory assumes that the solutions to which the lode minerals owe their existence have come from above. Such an origin can be considered for lode filling only where no manner of connection to eruptive phenomena is indicated and where the deposit accordingly is more or less a surface deposit. In this manner for instance small veins of iron ore are formed in limestone, most of which show but little

extension in depth. More important are the small cracks and veins which extend into the bed-rock below auriferous gravel-deposits and contain a little gold which has infiltrated from above. The noble metal in these cases was leached from the gravel-deposits by solutions of alkali carbonate.

Again, the veins of richer ore which as a result of migration of the metal content are not infrequently found penetrating from under the zone of enrichment some little distance into the poorer primary zone beneath, have also received their material from above.

(*b*) According to the ascension theory the solutions which fill fissures or produce impregnated zones rise from depth. Since such a procedure would usually stand in close connection to an eruptive magma, not only do aqueous solutions come into question but also the magma itself together with the vapours arising from it. This theory therefore embraces magmatic injection, pneumatolysis, and the action of heated water.

In connection with magmatic segregations, fractures in the country-rock may become filled with ore, such veins then appearing like apophyses from the main ore-body. This occurrence, illustrated in Fig. 16, is one of ascension. If in addition a portion of the eruptive magma itself were found within the fracture it would be justifiable to regard the occurrence as an injection.

In the case of the tin lodes it is assumed that the so-called tin minerals have been formed by the action of gases and vapours arising from magma still molten in depth. As gases and vapours are here concerned rather than solutions the procedure in error is spoken of as mineral formation by sublimation though the more proper term is pneumatolysis. In volcanic craters the deposition of sulphur in fissures and impregnated zones is often considerable, and sufficient in the cases of many extinct volcanoes to form the basis for profitable mining. Such sulphur-deposits as these have also been formed by ascension.

The formation of lodes from aqueous solutions is however of far greater importance. These solutions in most cases represent the later phases of eruptive phenomena since they are sometimes in close and sometimes in distant connection with an eruptive magma. The contact-metamorphic lodes and some others, especially those of the quicksilver and young gold-silver groups, stand in easily traceable connection with eruptive rocks, while with those of the old gold group and the sulphide lead-zinc lodes there is generally only the presumption that the mineral-bearing solutions may be referred back to an eruptive magma.

(*c*) In only comparatively few cases is there direct proof that the depositing solutions have no relation at all to eruptive activity. The deposits which have been formed by lateral secretion are among these.

The essential nature of these deposits is that the metal which has become concentrated within them formerly existed chiefly in the form of silicates uniformly distributed throughout the country-rock, from whence it has become leached and re-deposited in fractures. While formerly, following the example of Sandberger, the lateral secretion theory was applied to the explanation of numerous groups of lodes, after the careful research of Stelzner it can now only with certainty be held to be free from objection in one case, namely, that of the veins of garnierite and asbolane. With

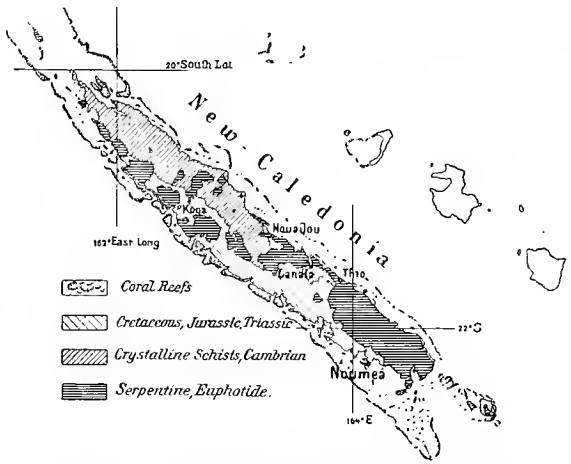

FIG. 156.—Distribution in New Caledonia of the serpentine rock carrying the veins of garnierite and asbolane.

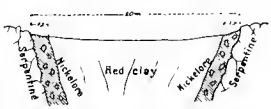

FIG. 157.—Section of the garnierite deposit of New Caledonia showing the relation of such a deposit to the serpentine and the resultant red clay.

these veins lateral secretion proceeded as follows. Nickel being one of those elements associated particularly with basic rocks and especially with peridotite, the first stage in the concentration of the nickel may be said to have been that of magmatic differentiation, which however did not proceed far enough to form a useful deposit. Apparently in New Caledonia and at Frankenstein in Silesia, etc., hot springs still further decomposed the serpentinized peridotite, leaching the nickel content to deposit it again in fractures as the hydrous nickel-magnesium silicate, garnierite. The occurrence in New Caledonia is illustrated in Figs. 156, 157. At Malaga it is probable that the occurrence of this nickel mineral has resulted from the decomposition of niccolite.

Similarly cobalt becomes concentrated in the form of asbolane although primarily it occurred together with the nickel in the olivine. When describing these deposits of garnierite in a subsequent chapter the separation of the two elements to form separate deposits is discussed.

The different stages in the formation of these deposits may therefore be said to be:

1. The concentration of the nickel in basic eruptive rocks and especially in peridotite.
2. The extraction of this nickel by heated waters.
3. The deposition of the hydrous nickel-magnesium silicate in veins.

On the Surface: Sedimentation.

The formation of ores by precipitation on the earth's surface may be studied to-day in the lake- and bog-iron ores, further reference to which is made in a subsequent section wherein the recent and interesting work of the Finnish chemist, Ossian Aschan, is discussed. To this group belong also the deposits of manganese nodules found and investigated in many seas by means of deep-sea dredging. Both these classes of deposit are of oxidized ferro-manganese ores.

Under other conditions a deposition of sulphide ore takes place. The formation of ferrous sulphide in the mud of the Black Sea is well known. The water near the bottom of this sea, probably from the reducing effect of sinking organic remains or of bacteria upon the sulphates present, contains sulphuretted hydrogen which precipitates the ferrous sulphide. This occurrence is mentioned again later when discussing the deposits of sulphide ores.

In addition and as shown by E. Kohler,[1] the phenomena of adsorption are important factors in the formation of many deposits, especially those deposited from sea-water. By adsorption—which must not be confused with absorption—is meant the phenomenon whereby such substances as charcoal, gelatinous silica, clay, and kaolin, take within their mass gases, metal-salts, etc., with which they come in contact. If for instance a pulp of clay or kaolin be added to an aqueous solution of copper sulphate, this salt will become adsorbed in the sinking particles; so searching is this action that even the smallest amount of the copper salt in this manner becomes precipitated. It must not be overlooked however that under certain conditions adsorption is accompanied by a chemical change.

Sedimentation postulates conformity, that is a regular or in any case a uniform deposition over a certain area. It is exemplified by the coal seams which maintain approximately the same thickness, the

[1] *Zeit. f. prakt. Geol.*, 1903.

same percentage of ash, etc., over large areas. With metalliferous deposits however, though as illustrated in Fig. 158 this conformity may be extensive, it is usually more limited since their formation is more or less dependent upon local circumstances. Lake-ores for instance are not usually distributed regularly over the entire bottom of a lake but only in particular parts.

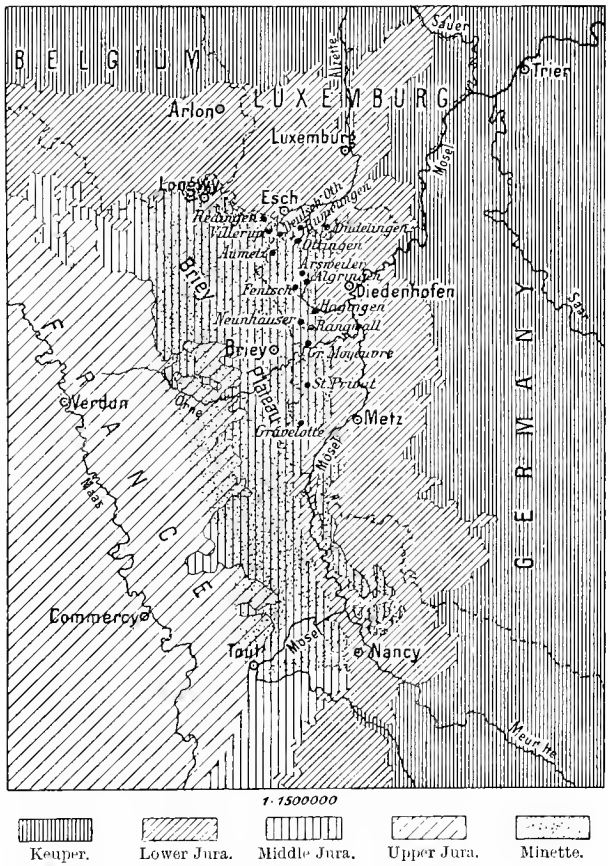

FIG. 158.—Conformable and flatly-bedded minette bed.

It is therefore not surprising that sedimentary ore-deposits often pinch out fairly quickly. It was formerly considered that conformity in an ore-deposit was a sufficient indication of a sedimentary formation, but this view, as may be gathered from Fig. 159, can now no longer be maintained.

Recent investigation has shown that metasomatic alteration often limits itself to particular layers of a formation whereby a deposit is formed having great regularity in strike and dip. Such a deposit may indeed to all

appearances be a sedimentary deposit though the ore was introduced long after the sedimentation. The Norwegian pyrite deposits also, which according to the latest investigations of Norwegian geologists are to be regarded as magmatic injections along certain bedding-planes, show in places a certain conformity to beds in the hanging- and foot-walls, so that in error they were formerly often considered as sediments. It follows

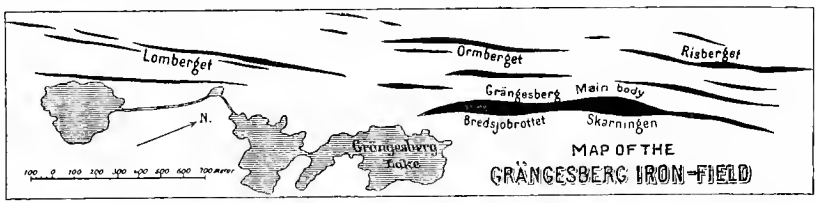

FIG. 159.—Conformable iron ore beds not of sedimentary origin exhibiting steep bedding. The country-rock is of old schists.

from these instances that it is often most difficult to determine whether a conformable ore-deposit is, or is not, of sedimentary origin.

A number of iron deposits are of undoubted sedimentary origin, such for instance as the Tertiary ores corresponding to the recent lake- and bog ores; many oolitic ores of the Jurassic and other formations; the carbonaceous and clay-iron ores, etc. With these also itabirite or ferruginous mica-schist may certainly be classed. On the other hand a number of bedded or apparently bedded occurrences of magnetite and hæmatite in crystalline schists, must now be considered as epigenetic in character though formerly regarded as sediments. An occurrence of such deposits is illustrated in Fig. 159.

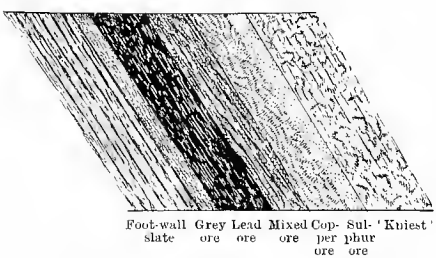

FIG. 160.—Conformable sulphide bed with overturned bedding. Rammelsberg.

The *Kupferschiefer* of the Zechstein formation is regarded by many authorities as a typical example of a sedimentary deposit of sulphide ore, though Beyschlag and Krusch have come to the conclusion that the copper is younger than the sedimentation of the bituminous marl. The *Knotten* ore-bed at Kommern, illustrated in Fig. 161, is also conformable although the secondary nature of the ore within it has been completely established. In the precipitation of ore within sandstone, adsorption often plays a material part.

6. The Formation of Ore-Deposits by Mechanical Concentration: Detrital Deposits

While most ore-beds were formed by deposition from solution, the detrital deposits formed by the mechanical rearrangement of older occurrences though having equal right to be termed ore-beds, occupy a place by themselves. These may be divided into detrital deposits in the narrower sense and into gravels, though between the two classes there is no genetic

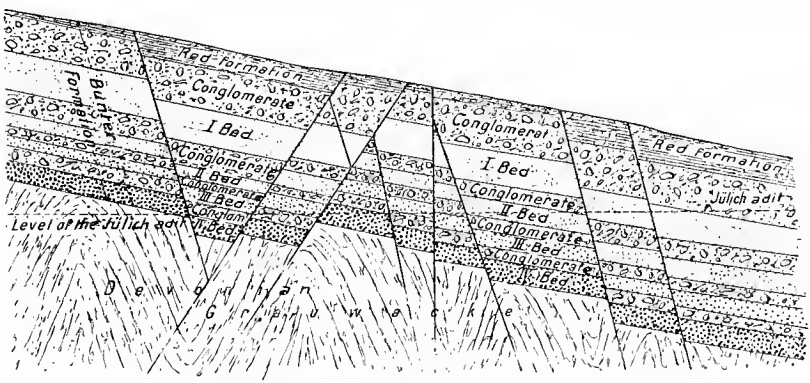

Fig. 161.—Nodular ore-bed at Kommern on the northern border of the Eifel. Conformable galena bed resulting from secondary impregnation of certain sandstone beds.

difference. While the gravels lie immediately on the surface or under a thin covering only, the detrital deposits may be covered by a considerable thickness of younger beds. The difference therefore is usually one of age, the detrital deposits being generally older than the gravels, which in fact belong either to the Alluvium or Diluvium periods.

With both classes of deposit only the last stage in the process of formation is known, namely, the disintegration of an older bed by the mechanical action of water and the concentration of the material to form the new deposit.

THE ABSOLUTE AND THE RELATIVE AMOUNTS OF THE METALS IN USEFUL ORE-DEPOSITS

LITERATURE

J. H. L. Vogt. 'Ueber die maximale Grösse der Erzlagerstätten,' Zeit. f. prakt. Geol., etc.

In estimating the economical importance of an ore-deposit it is not sufficient that the ore likely to be present be calculated with all possible care but the question must also be put as to the position the deposit under consideration takes among analogous deposits. The discussion of such a subject is however only possible when the exhausted as well as the existing occurrences are known, so that the size of the particular deposit may be the better appreciated by comparison. With this in view the figures of some of the known ore-deposits are given in this chapter.

Iron Ore.—The finest and richest single deposit yet known and investigated is that of Kiirunavaara-Luossavaara in northern Sweden. This magnetite deposit extends on both sides of the Luossajärvi Lake as an interrupted elongated elevation, this prominent position having resulted from the more complete erosion of the less resistant acid porphyrytic rock in which the deposit occurs. According to official reports the quantity of ore above the level of the lake is from 233–292 million metric tons consisting chiefly of Thomas ore with 63–64 per cent of iron. Every further metre in depth is estimated to contain 1·4 million tons of additional ore so that, reckoning to a depth of 300 m., approximately 700 million tons would be available. According to a magnetic survey a continuation of this deposit for a depth of perhaps 2 km. may be presumed, to which depth 2500 million tons would be contained, a figure which at the present however is only of theoretical interest. If again it be remembered that in the past a tremendous quantity must have been eroded, the original quantity of ore may be put at about 3000 million tons containing about 2000 million tons of metallic iron. The yearly production since 1903 has been from 1·2 to 1·5 million tons. It has however been decided to increase this to 3·3 million tons within a few years.

In the case of the famous occurrence at Gellivare having a yearly production of approximately 1,000,000 metric tons, it is reckoned that every metre of depth contains about 550,000 tons of ore; at Ekströmsberg and at Svappavaara — both lying in the neighbourhood of Kiirunavaara—200,000 and 180,000 tons respectively; and at Grängesberg in middle Sweden about 140,000 tons. Every single mine in the numerous though relatively small fields of Dannemora, Persberg, Striberg, etc., in middle Sweden, produces from 5000 to 20,000 tons per metre of depth, and some still more. Leaving Grängesberg out of consideration these mines of middle Sweden have produced some 70 million tons spread over several centuries. Similarly the mines near Arendal in southern Norway during a period of roughly 250 years have produced about 2·3 million tons of iron ore.

The most important deposit of iron ore in Central Europe is the celebrated Minette occurrence in German Loraine, Luxemburg, and the adjoining departments of Meurthe and Moselle in France. The pisolitic ores of this occurrence, which is illustrated in Fig. 58, are found in the beds of the Lower Oolite. The total amount of ore reckoned to be present in an area 100 km. long and 10–20 km. wide is 2000 million metric tons which, containing 36 per cent, is equivalent to 700 million tons of iron. Although the amount of ore and more particularly the amount of iron in this deposit does not nearly reach that of the Swedish deposits mentioned above, the amount of lime in this ore is especially advantageous, and the deposit will in any case guarantee the existence of the iron industry in Germany for a long period.

From the metasomatic deposits of iron ore in the Lower Cretaceous beds of the Bilbao district in Spain, till the end of the year 1907, about 150 million metric tons of ore—siderite, hæmatite, and limonite—containing an average of 50–52 per cent of iron, had been won, and though some of the deposits are now exhausted, the yearly production is still maintained at about 5 million tons. In this district within an area 25 km. long and 5–10 km. wide, approximately some 250 million tons of payable ore containing 125 million tons of metallic iron were present.

If the most important deposits of iron ore now being worked be compared, it is seen that though quite a number of them contain or did contain 10–20 million tons of ore, but few reached 100 million, and those which contained 1000 million tons must be regarded as rarities. A detailed review of the available quantities of iron ore in different countries was given before the International Geological Congress in Stockholm in 1910.

Manganese Ore.—The most important deposits of this ore yet known are those of Tschiaturi near Kutais in the Caucasus, and of Nicopol on the river Dnieper, both in Russia. A few years ago the available ore of the

first of these deposits was reckoned at 98 metric million tons and of the second at 7·5 million tons.

Copper Ore.—The deposits of copper ore do not by a long way reach the gigantic dimensions of the occurrences of iron ore. Further, since the copper content is generally low and varies considerably from one deposit to another, the copper statistics generally have reference to the total quantities of metallic copper rather than to figures of ore. In the following examples therefore, figures of metallic copper only are given.

Röros in Norway, with smelting ore containing 4–6 per cent of copper, has from the beginning of work in 1644 to the year 1907 produced about 80,000 metric tons of metallic copper in addition to pyrite containing 10,000 tons, making 90,000 tons in all, having a value of about £7,500,000. At Fahlun in the Swedish province of Dalarne, work was begun in the thirteenth century since which date, and from ore containing now about 3·5 per cent of copper, 500,000 tons of metallic copper, in round figures, have been produced which, with the gold and silver contained, represents a total value of about £55,000,000. The period of highest production was in the middle of the seventeenth century when, in the year 1650 for instance, 3455 tons of copper were produced. At the present time when the production has sunk to one-tenth of this amount the mine keeps up its existence by working the poorer portions refused in former years.

The most important occurrence of copper ore in middle Europe is that of the *Kupferschiefer* of Mansfeld, which belongs to the Lower Zechstein of the Permian system, wherein it lies conformable. This deposit consists of a bituminous shale carrying about 3 per cent of copper and 150 grm. of silver per ton for a width of 25 cm. In addition there are however two other occurrences of ore, one above and one below, which following faults are neither regular nor conformable. The production of copper at Mansfeld from 1779 to 1877, amounted to 130,000 tons; from 1878 to 1893, to 180,000 tons; from 1894 to 1907, to 280,000 tons; making from 1779 to 1907, a total of 590,000 tons. If the still earlier production be included the production of this field may be put down as two-thirds of a million tons of copper. In consequence of the comparative regularity of the distribution of the copper it is possible and pertinent to reckon the amount of this metal contained per unit of area. This amounts to approximately 10,000 tons of copper per square kilometre. Using this figure there existed originally in this relatively poor *Kupferschiefer* of the Mansfeld syncline, several million tons of copper.

In the celebrated Lake Superior district of North America the copper occurs entirely native, either filling vesicles, veins, and pockets in melaphyre, or as the matrix of a quartz-porphyry conglomerate in a rock complex lying unconformably upon the Potsdam sand-

stone of the Upper Cambrian, and covered by pre-Silurian sandstone. The largest mine working this deposit, the Calumet and Hecla, having a present depth of 1400 m., from 1868 to 1907 produced 750,000 tons of copper. The other mines from the commencement of work in 1845 have together produced about 690,000 tons, so that the production of the whole district hitherto has been about 1·5 million tons. Many of these mines are now considered exhausted. Speaking generally the amount of copper still to be obtained from the Calumet and Hecla may be put at 1·5 million tons, and that of the entire district at 2·2 million tons.

The Anaconda Mine of Butte, Montana, is working one of the richest and most celebrated copper deposits of the world where the occurrence is that of composite lodes in a country-rock of granite, and in the neighbourhood of rhyolite intrusions. From the beginning of the work in 1880–81 till 1907 these mines produced not less than 1,970,000 tons of copper, while the amount of ore now considered to be present in the deposit is estimated at several million tons.

Undoubtedly however the most important of all copper deposits yet known are those occurring in the district of Rio Tinto or Huelva in the south of Spain, from whence in ancient times 20–30 million tons of pyrite and copper ore may be considered to have been produced. Since the middle of the nineteenth century approximately 40 million tons of pyrite containing 3 per cent of copper have been produced, and according to a calculation made in 1895, a further amount of 135 million tons was then present in the neighbourhood of Rio Tinto alone. It may be reckoned therefore that in the three or four principal mines of Rio Tinto there were originally about 200 million tons of pyrite containing 4–5 million tons of copper. If to this be added the amount calculated to have been originally present in the mass which has been removed by erosion, and the further amount still existing in depth, the figure of 400 million tons of ore containing at least 8 million tons of copper is reached.

The numerous other pyrite deposits in southern Spain and Portugal are considerably smaller. Some nevertheless originally contained 20–50 million tons, that is 1·5 million tons of copper, though most did not contain more than 10 million tons. The total production of the Tharsis Company, working five or six large mines, two of which however are now practically exhausted, from 1868 to 1907, was 375,000 tons of copper, while that of the St. Domingo Company with only one large mine, from 1859 to 1907, was 190,000 tons. The total production of the remaining mines in southern Spain since the middle of last century amounts to about 150,000 tons of copper, to which however must be added a considerable amount won previously. It is of importance and interest to remember that these large cupriferous pyrite deposits, consisting

almost one-half of sulphur, represent at the same time the most important deposits of sulphur in the world.

The total production of Cornwall, the most important copper district in England, from 1726 to 1800, amounted to 350,000 tons; from 1801 to 1845, to 555,000 tons; from 1846 to 1853, to 150,000 tons; from 1854 to 1893, to 240,000 tons; and from 1894 to 1906, to 7000 tons; or altogether from 1726 to 1906, to 1·3 million tons. Including an amount to represent that produced earlier than these dates, the total production of Cornwall may be estimated at 1·75 million tons, though thereby the copper available in the mines down to depths of 500–800 m. has practically become exhausted.

The better known of the copper deposits of Russia and Siberia, those for instance at Perm, Ural, Kedabek in the Caucasus, etc., have together produced about one million tons of copper. Those in Perm are now practically exhausted. The numerous copper deposits found almost all over Chili produced up to the end of the last century about two million tons of copper. In doing this however the pace was so forced that many of the deposits are now exhausted and others are not far from being so, a condition of affairs reflected in a present production of 20,000–30,000 tons per year against 50,000 tons previously.

The total production of the numerous mines in Japan from 1881 to 1907 amounted to 520,000 tons. During the previous 250 years it is stated that a yearly production of about 2800 tons was maintained, making altogether about 1·25 million tons of copper to date, though the data employed in this computation require confirmation. The production during recent years has risen considerably, a sign that the quantities available are far from exhausted.

Copper mining in South Australia which began in 1841 had not, up to the year 1900, produced 300,000 tons of copper. Two-thirds of the production comes from the districts of Moonta and Wallaroo. The Burra-Burra Mine, where cuprite is the principal ore, produced from 1845 to 1877 about 52,000 tons. From the copper mines of New South Wales up to 1897 a total of 122,000 tons had been won.

According to the above data the most important copper deposit in the world, the Rio Tinto, contained originally 8 or at most 10 million tons of copper and it appears questionable whether there exists any larger copper deposit; only a few deposits contained as much as one million tons, and many famous and important mines were completely exhausted after producing from 250,000 to 500,000 tons, so that occurrences with a total of 100,000 tons must be regarded as noteworthy. In many cases the original amount did not reach 25,000 tons and many smaller mines, some of which may have been in operation for more than a hundred years, produced less than 10,000 tons.

Owing to the high value of metallic copper the average copper content of the ores mined is comparatively low. The following statement is taken from figures arrived at by Vogt in 1895. In this the copper content refers in each case to the ore hoisted, in which a good deal of the country-rock, unavoidably broken with the ore, is also included. Allowance has been made for all losses in concentration, smelting, and extraction, these losses by any rational system of treatment being such that the original content of the ore is usually about 25 per cent higher than the figures given, these representing the amount recovered.

Montana . .	Butte, 1890	3 per cent plus a little silver.	
Lake Superior .	Calumet and Hecla	2·5–3·00	
	Tamarack	2·5–2·75	
	Quincy	2·0–2·70	
Australia . .	Moonta	2·00	
Japan . .	Ani., 1891	1·93	
Spain . . .	Rio Tinto	1·75	plus sulphur in pyrite.
	Other mines	1·0–1·66	
Norway . .	Sulitjelma	1·7–1·80	
	Röros	1·0–1·80	
	Aamdal	1·3–1·40	
Sweden . .	Fahlun, 1850–74	1·2–1·25 plus gold.	
Finland . .	Orijärvi, formerly	1·20	
Lake Superior .	Kearsage, 1889–92	1·2–1·40	
	Franklin, 1887–93	1·0–1·30	
	Osceola, 1886–91	1·0–1·30	
	Atlantic, 1880–91	0·6–0·70	
Germany . .	Mansfeld	0·60 plus silver.	

With the lodes and beds of smaller dimensions the copper content per square metre upon the plane of the deposit, provides some basis of comparison. In Mansfeld this is 10 kg. of copper and 50–60 grm. of silver; at Aamdal in Norway about 50 kg. of copper; and at Sulitjelma 100–125 kg.

Deposits which, having considerable extent in strike and dip, contain 3–4 per cent of copper must be accounted rare. More generally the ore hoisted contains 1·5–2·25 per cent, and many well-known mines even produce ore with 1–1·25 per cent and less. Of the 435,000 tons of copper produced in 1898, after sorting and concentration:

75,000 tons were from ore containing less than 4 per cent copper.			
125,000	,,	,,	4–6 ,,
45,000	,,	,,	6–10 ,,
30,000	,,	,,	10–25 ,,
15,000	,,	,,	25–70 ,,
75,000	,,	,,	75 ,,
70,000 tons were from ore containing an unknown percentage.			

Speaking generally, one-sixth of the copper production is obtained from native copper, and one-third to one-half or more from chalcopyrite in pyrite, the balance being made up by the various other ores.

Silver Ore.—The mines at Kongsberg in Norway from 1624 to 1907 produced about 960 tons of silver having a value of about £8,000,000; the famous lodes of Freiberg from 1163 to 1890 produced 5057 tons having a value of about £44,400,000; the Comstock lode, now regarded as almost exhausted, from 1859 to 1889 produced about 4820 tons of silver and 214 tons of gold with a total value of about £68,000,000.

More excellent still are the results from some of the famous old mines of Peru, Bolivia, and Mexico. The production of the Veta Grande, Zacatecas, alone, from 1548 to 1823, has been reckoned at 14,000 tons of silver valued at £115,000,000. The total production of Potosi in Bolivia during the period 1545–1789 was reckoned by Alexander von Humboldt to have been about 15,000 tons or £122,000,000; while A. F. Wendt reckoned that the total production from the beginning in 1540 to the end in 1809 was not less than 30,000 tons or more than six times the production of Freiberg and Comstock together.

When considering these figures of production however it must be remembered that all kinds of losses occur in the winning of silver, that only the richer ores were worked, and that the mines generally were not exhausted in depth. Totals of production are therefore in general considerably lower than the quantity of metal originally concentrated in the deposits concerned. In spite of this the figures given above allow it to be said that occurrences containing more than 10,000 tons of silver, that is twice the amount of the Comstock production, within one mine or within one closely-bounded mining district, must be accounted rare, while mines with 5000 tons or 10,000 tons are also quite uncommon. If however whole districts such as those occurring in Mexico and in Bolivia be considered, higher figures will naturally be obtained.

Gold Ore.—The total production of the United States from 1845 to 1906 amounted to 4286 tons of metallic gold having a value of close upon £600,000,000. That from Australia from 1851 to 1906 was 3986 tons or not quite so much as that from the United States. In contributing to these amounts however the gravel-deposits, which were largely responsible for the rapid rise in the production, became as is well known completely exhausted, so that the present production comes substantially from lodes and but little from such gravels.

The Comstock lode in Nevada, alone, from 1859 to 1889, produced 214 tons of gold with 4820 tons of silver. At Cripple Creek in Colorado, where in 1891 the telluride ores were discovered, the mines up to the end of 1905, from within a circle having a radius of 3 km. and to a maximum shaft-depth of 400 m. produced, according to W. Lindgren, gold to the value of approximately £26,000,000, corresponding to 190 tons, which amount up to the end of 1907 had increased to 235 tons.

The different lodes of the Kalgoorlie district, Western Australia, were reckoned by Krusch [1] to contain the following quantities of gold in 500 feet of length and 1000 feet of vertical depth:

No. 4 lode,	Golden Horseshoe	10·288 tons.
No. 4 „	Great Boulder	4·436 „
No. 3 „	Golden Horseshoe	4·058 „
No. 3 „	Perseverance	3·645 „
No. 3 „	Lake View	2·700 „

These figures pertaining to a comparatively small lode-section are interesting and valuable especially when compared with others similarly obtained from the Witwatersrand where generally within such a section all the ore-beds, there known as ' reefs,' together contain but 5·5 tons of gold. This comparison however is not complete without taking into consideration the fact that the above-mentioned lodes in Australia are practically vertical while the Witwatersrand conglomerate beds dip about 45° at the outcrop and 25° in depth, the effect being, that whereas at Kalgoorlie the distance on the lode-plane practically coincides with the true vertical depth, with the Witwatersrand reefs the distance upon the reef-plane represents the hypotenuse of vertical depth, this latter being about 2·3 times less, so that to make a comparison with the lodes in Western Australia, this figure of 5·5 must be divided by 2·3. The figure of 2·5 tons thereby obtained represents the amount of gold in a reef section upon the Witwatersrand, 500 feet long and 1000 feet deep, upon the plane of the reef. This figure would be still more unfavourable if each one of the conglomerate beds were considered by itself. As it is, it is seen that all of them together do not, in so far as the quantity of gold contained is concerned, reach the figures of the particular deposits of Australia mentioned.

If we assume that the lodes of the Great Boulder, the Ivanhoe, and the Golden Horseshoe, which together form a connected lode-series about 350 feet long, maintain the above-mentioned values to a depth of 1000 feet the amount of gold contained would be 400 tons. This assumption has however been found by the experience of the last year or two, not to be tenable, as the mines appear to become poorer in depth and the figure of 400 tons is therefore without doubt too favourable. Since however this complex of gold lodes is one of the richest in the world the statement is justified that only in the rarest cases is an amount of 400 tons of gold concentrated in one lode or in one series of lodes.

In this connection however the auriferous beds of the Witwatersrand are unique. Reckoning a length of 40 km., L. de Launay estimated that to a depth of 1000 m. there was an amount of 4000 tons of gold, and to 1473 m. an amount of 6000 tons. With these figures those

[1] *Zeit. f. prakt. Geol.*, 1903, p. 247.

of Hatch and Chalmers agree, their estimate being 5000 tons to a depth of 1600 m., a result which Becker considered not exaggerated. Since also the tilting of these beds from their original horizontal position took place subsequent to the introduction of the gold, there is nothing to justify the assumption that the gold content will cease at a depth of 1000 m. With gold lodes on the other hand depths of even 1000 feet are already critical.

Quicksilver Ore.—From statistics collected relative to quicksilver mines it is seen that the most important of these deposits carry more than 100,000 tons of that metal. In Idria for example, from the years 1525 to 1900 about 60,000 tons of quicksilver were produced, and it is estimated that there still remain 30,000 tons in reserve. Leaving out of consideration the poorer portions of the deposits, the losses in treatment, and the further extension in depth, it may be said that 100,000 tons of quicksilver were originally concentrated here.

The finest quicksilver deposit in the world is however Almaden which during the period 1564–1900 and down to a depth of about 360 m., produced about 160,000 tons of quicksilver. Allowing for losses in treatment and for the fact that the deposit becomes richer in depth, it may be reckoned that to a depth of 500 m. from 250,000 to 330,000 tons of quicksilver were here deposited, which amount if a depth of 1000 m. be allowed becomes increased to 500,000 or 660,000 tons. The possibility of finding a deposit anywhere containing one or more million tons would therefore appear to be excluded; while even deposits of 100,000 tons are very seldom encountered. Huancavelica in Peru, from 1571 to 1825 when the mines ceased working, produced about 270,000 tons; and New Almaden in California, from 1850 to 1897 produced 34,000 tons. The last-named mine, which in 1885 was already 650 m. deep, is now on the down grade. A large number of quicksilver mines cannot even substantiate an original quantity of 10,000 tons.

At Almaden where the deposit is exceptional, not only quantitatively but also qualitatively, the ore hoisted usually contains 7 per cent of quicksilver. Most deposits however contain but from 0·5 to 2 per cent, and seldom from 2 to 4 per cent. Though quicksilver deposits are less frequent than those of silver, when they do occur they are usually much greater; some are even five to ten times as large as the most important silver deposits. Quicksilver is also more concentrated in its deposits than silver. A quicksilver content of 0·5 to 1 per cent in a useful deposit would not be regarded as high grade though a similar silver content would be regarded as very rich.

Tin Ore.—The lodes in Saxony and Bohemia, worked from the Middle Ages and so well known mineralogically and geologically, have produced

roughly 100,000 to 125,000 tons of tin, though this estimate is not entirely reliable. Work upon them has now almost entirely ceased. Cornwall including Devon produced from its own ores and during the period 1801–1907 about 665,000 tons of tin; before that time according to one estimate at least 600,000 tons were produced, while according to another estimate the amount was more than one million. The total production of this district may in any case be put down at from 1·3 to 1·6 million tons; the yearly production which between the years 1860 and 1890 was almost 10,000 tons, has latterly sunk to about 4500. Australia between 1872 and 1907 produced about 240,000 tons, though the present production is not so high as it was in the year 1880.

By far the most important occurrence of tin is that in the Straits Settlements including Banka and Billiton. From the deposits here included 1,700,000 tons of tin were won between the years 1821 and 1907, practically all from gravel-deposits. The present yearly production, which is still rising, is about 70,000 tons. The tin or tin-silver lodes of Bolivia from 1883 to 1907 produced about 110,000 tons.

All these figures show that districts which have contained more than one million tons of tin in payable ore are of great rarity. Even such a famous old district as that of the Erzgebirge of Saxony and Bohemia, has not produced a quarter of a million tons. The tin gravels of the Straits however, distributed over districts often widely separate, undoubtedly originally contained several million tons of tin. Data regarding the relative amounts of tin in tin lodes are given later in the particular section describing these lodes. It need only here be remarked that tin in its primary deposits does not, either absolutely or relatively, occur less plentifully than copper.

Zinc- and Lead Ores.—The data available for estimating the metal quantities present in the important deposits of these ores is very insufficient. Such estimates consequently appear only to have been possible with the long-known zinc deposits of Silesia, the Rhine, Belgium, and Sardinia.

Nickel Ore.—This metal in so far as its useful application is concerned is comparatively recent and it is only since the first half of last century that from a mining point of view it has received closer attention. Arsenical nickel ores in lodes appear so far to be limited to the occurrences at Dillenburg, Dobschau, Schneeberg, the cobalt lodes in the Zechstein, and the new occurrences in the Coleman district of Canada. On the other hand the nickel-pyrrhotite deposits in Canada from 1888 to 1907 produced altogether 60,000 tons of nickel, and the similar Norwegian deposits from 1848 to 1907 about 4500 tons. In addition, from 1879 to 1907, about 75,000 tons were produced from the garnierite deposits of New Caledonia.

From these and other figures it may be said that nickel is rarely found

concentrated to an amount over 50,000 tons in one payable ore-deposit. Even deposits considered relatively large do not contain as much as 10,000 tons. It is indeed striking that nickel in spite of its more or less considerable distribution in the basic rocks never, or very seldom, forms important deposits. In fact it is in general not so well represented in the deposits as copper, though the amount of this latter metal distributed throughout the solid crust is substantially smaller.

Cobalt Ore.—The ores of this metal usually occur much less abundantly in deposits than those of nickel, a relation in harmony with the fact that within the earth's crust cobalt generally has only about one-tenth the relative abundance of nickel. While from 100 tons of ore hoisted from many nickel-pyrrhotite deposits now being worked, 1·25–2 tons of nickel is generally obtained, from 100 tons of cobalt ore hoisted from the mines at Modum in Norway during the period 1873–1894 and after deducting the losses in sorting, concentration, and smelting, only 0·08–0·1 ton of cobalt resulted. The asbolane deposits of New Caledonia, though exact figures are not available, are richer than this. The cobalt content in the lodes associated with the occurrences of copper slate at Riechelsdorf, Schweina, etc., is also low; and whether the smaltite lodes lately discovered in Canada will fulfil the great expectations yet remains to be seen.

Chromium Ore.—Details concerning the quantities of this ore in its deposits are given when discussing the chromite deposits.

The metal recovered from 100 tons of ore hoisted, after subtraction of all the losses of dressing and metallurgical treatment, often varies from year to year in one and the same mine. With different mines producing ores of the same metal the amount recovered, as already demonstrated in the case of copper, varies greatly. In consequence it is not possible to put forward such average figures for the different metals as may always be applicable. The following table giving the usual minimum and maximum figures of net yield per 100 tons of ore hoisted, obtained in most cases from deposits now being worked, will nevertheless be found interesting:

Iron	30·00–50·00 tons.
Manganese	15·00–25·00 ,,
Chromium	10·00–20·00 ,,
Lead, with or without silver	15·00–25·00 ,,
Zinc	6·00–12·00 ,,
Copper	1·25– 2·25 ,,
Tin, from lodes	0·75– 1·50 ,,
Nickel, from pyrrhotite	1·25– 2·00 ,,
Cobalt, from its arsenides	0·10 ,, and more
Quicksilver	0·75– 1·75 ,,
Silver	50·00–200·00 kg
Gold, from lodes	1·00– 2·00 ,,

With some particularly rich deposits these figures are exceeded. For instance at Kiirunavaara from 100 tons hoisted, 96 tons of iron ore and approximately 60 tons of iron are recovered; at Almaden 7 tons of quicksilver from 100 tons of ore hoisted. On the other hand there are deposits which in consequence of particularly favourable conditions are still payable, though their metal content may be considerably below the figures mentioned.

The following statistics of the world's production and the prices of the more important metals at different times since the year 1800, form a useful supplement to the statements within this chapter.

World's Production of the more important Metals

Metric Tons

	1800.	1850.	1870.	1880.	1890.	1900.	1907.
Iron	0·8 [1]	4·2	12·0	18·5	27·4	41·0	59·1 [2]
Lead	± 30,000	150,000	290,000	390,000	540,000	873,000	990,000
Zinc	?	± 55,000	120,000	220,000	350,000	480,000	740,000
Copper	± 20,000	57,000	110,000	155,000	275,000	495,000	720,000
Tin	± 4,000	10,000	20,000	40,000	55,000	85,000	100,000
Nickel	Nil	± 100	± 500	± 750	2,400	7,500	14,000
Aluminium	Nil	Nil	Nil	± 10	175	7,500	20,000
Quicksilver	± 1,000	± 1,750	2,800	3,950	3,900	3,300	3,700 [2]
Silver	800	800	1,750	2,500	4,400	5,600	5,600 [3]
Gold	18	100	161	160	181	392	613 [2]
Platinum	?	0·5	2	3	3	5·5	6 [3]

[1] In million tons. [2] 1906. [3] 1905.

Latterly the yearly outputs of some of the more important ores have been:

Iron ore	some 130,000,000 tons.
Manganese ore	1,000,000 ,,
Chromium ore	75,000 ,,
Arsenic ore	15,000 ,,
Antimony, metal	7,500 ,,
Wolfram ore	3,000 to 4,000 ,,
Molybdenum ore	100 to 200 ,,
Cobalt, metal, in cobalt compounds	100 to 200 ,,
Bismuth, metal	probably 200 ,,
Cadmium	20 ,,

The world's production of those metals which are more important in the manufactures namely, iron, lead, zinc, copper, and tin, has roughly doubled itself fairly regularly in periods of about twenty years, though with some metals, copper for instance, the increase has of late been at a greater rate. A similar rapid advance may be assumed for the present and following decades. With such metals as have more recently found application in the manufactures, nickel and aluminium for instance, the advance is and will be more noticeable than with those which have long

been applied. On the other hand the production of silver, since the great drop in price in 1893 and 1894, has remained practically constant, which since the close of the late 'seventies has also been the case with quicksilver.

Prices in Shillings per Kilogram

	1850.	1860.	1870.	1880.	1890.	1895.	1900.	1905.	1907.
Iron	0·044	0·054	0·054	0·055	0·048	0·045	0·069	0·053	0·055
Lead	0·35	0·44	0·37	0·33	0·27	0·21	0·34	0·28	0·38
Zinc	0·31	0·38	0·36	0·36	0·45	0·29	0·40	0·50	0·47
Copper	1·70	2·05	1·40	1·36	1·19	0·88	1·47	1·40	1·70
Tin	1·60	2·60	2·50	1·75	1·90	1·25	2·60	2·80	3·40
Nickel	...	± 8	8	7	4	2·50	3·00	3·25	3·25
Aluminium	...	± 100			15	3·00	2·00	3·25	3·25
Quicksilver	6·00	4·25	4·75	3·75	5·25	3·90	5·25	4·25	4·00
Silver	180	182	180	155	142	87	83	82	89
Platinum	...	...	635	960	1900	1475	2400	3000	3500

In addition the following prices have of late years been paid for other less important metals and ores : for 1 kg. of metallic arsenic 1·20 shillings ; 1 kg. antimony 0·70–1·50 ; 1 kg. cadmium 4·0–6·0 ; 1 kg. bismuth 7·0–15·0 ; 1 kg. native sulphur 0·09–0·10 ; 1 kg. sulphur in pyrite 0·032–0·045 ; 1 kg. of manganese in manganese ore 0·08–0·12 ; 1 kg. chrome oxide in chromium ore 0·12–0·15 ; 1 kg. tungstic acid in wolfram ore 2·0–5·0 ; 1 kg. cobalt in cobalt ore 5·0–10·0 ; 1 kg. molybdenum sulphide in molybdenum ore 2·0–3·0 ; 1 kg. of thorium oxide in monazite sand about 25·0 ; and 1 kg. of rutile 0·60–0·75 shilling. These prices are naturally subject to considerable variation.

PRIMARY AND SECONDARY DEPTH-ZONES

Primary depth-zones are those genetically connected with the phenomena of a deposit's original formation and dependent upon those phenomena. They originate through changes in temperature and pressure when deposits were being formed by mineral-bearing solutions. Since the vertical measurements essential to a difference of pressure can only occur with steeply-inclined deposits, the occurrence of such primary zones is limited to lodes and magmatic segregations. With lodes the mineral solutions in greater depth naturally were under greater pressure than those nearer the surface, while with magmatic deposits where the vertical extension of the still molten deposit was considerable, a separation of the ores in response to differences of pressure and of temperature must likewise have taken place.

Primary differences in the character of the ore and in the nature of the mineral association are found with many lodes below the zones of secondary alteration and independent of those zones; and though in consequence of the comparatively shallow depths to which mining penetrates the cases where this is established are few compared with those where this has not been possible, these depth-zones are probably fairly general. It is but natural to assume that with temperature and pressure varying according to depth, lodes at a depth of several kilometres below the surface as it existed at the time of their formation would have a character quite different from that which they would possess near that surface. Depths of one and a quarter to one and a half kilometres below the present surface are to-day however seldom reached since by far the largest proportion of development work upon lodes does not extend to more than one-half, three-quarters, or at most one kilometre.

The occurrences mentioned below illustrate variations in primary deposition. The tin-copper lodes of Cornwall carry copper ore in their upper levels where the country-rock is chiefly slate, and tin ore in their lower levels within the granite where copper ores practically speaking no longer occur. B. von Cotta[1] mentions that in the neighbourhood

[1] Vol. I. p. 128.

of Seiffen, that is in the Erzgebirge gneiss, many lodes which carry tin in their upper levels become argentiferous copper lodes in depth. In the Clausthal district sphalerite increases in depth at the expense of galena, which latter preponderates in the upper levels. No sharp boundary however exists between the two classes of ore, one gradually taking the place of the other. It was formerly sought to explain the striking difference between the ore of the Clausthal lodes and that at St. Andreasberg as due to primary variation in depth, on the assumption that the varying distances of the lodes from the granite beneath had caused corresponding variations in deposition, the granite being further assumed in each case to have supplied the material. As however will be explained later the evidence at St. Andreasberg rather points to the secondary enrichment of poor previously-existing silver ores, which enrichment in consequence of tectonic phenomena has to-day the appearance of continuing to unusually great depths.

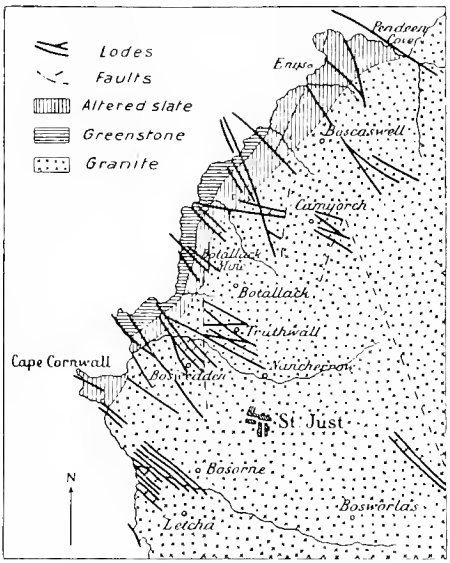

FIG. 162.—The tin-copper district of Cornwall. The lodes in altering their strike alter also their filling.

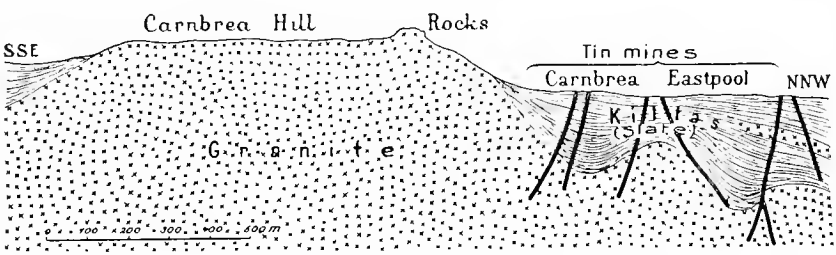

FIG. 163.—Tin-copper lodes in Cornwall carrying copper in the slate, and tin in the granite.

The change of the ore in depth experienced in the Oberharz may also be observed in the lodes of the Rhine slate country. While formerly lead ore chiefly was obtained from these, and but little zinc in depth the proportion between these two has strikingly altered in favour of the

latter. Below the sphalerite again, in the Castor Mine in the Berg district, siderite set in so quickly that shortly after its first appearance the deposit became unpayable. In this district therefore the sequence of depth-zones is first galena, then sphalerite, and finally siderite. The siderite lodes occurring in the Lower Devonian of Siegerland carry sulphides sometimes to a considerable extent, these including chalcopyrite, galena, and sphalerite. Further development has shown that these sulphide ores are limited to the upper levels and that siderite makes its appearance in depth, a change which in part must also be regarded as referable to primary deposition. In a mine near Argelèze-Gazost, on the north slope of the Pyrenees, galena is similarly replaced in depth by sphalerite, while according to the management, above the galena cassiterite was formerly occasionally found. A similar tin gossan has also been observed in the Freiberg district. The steeply-inclined copper deposits of the Rio Tinto district exhibit in the primary zone, below the gossan and the enriched zone, a gradual but constant decrease in the copper content, a decrease which is probably connected with the primary deposition. The tin lodes of Bolivia carry a good deal of stanniferous pyrite which becomes poorer in depth, an impoverishment which likewise appears to be primary in character.

Seeing that large magmatic segregations occur comparatively seldom, the evidences of such primary variations with this class of deposit are meagre. Judging from the figures of production from the nickel-pyrrhotite deposit of Sudbury, Canada, one of the most important of these occurrences, it would appear that both the copper content aud the nickel content fluctuate considerably in depth, such fluctuations probably being also primary.

Since pressure and temperature, which are regarded as causing these variations in primary deposition, generally promote the solubility of substances, those then which are the more easily dissolved would separate the less readily from solution and would consequently be found in the neighbourhood of the surface. This is probably the reason why minerals which form many easily soluble compounds are found in the upper levels. Again, differences in the filling of deposits, such as may be referred to change of temperature and pressure, may make themselves evident not only in the particular ores deposited but also in the internal structure of the deposit.

Primary depth-zones are naturally often connected with impoverishment or enrichment. Nor are they confined exclusively to the ore, they occur also with the gangue, although the observations in this connection have so far been few. Calcite for instance in some districts is found to a large extent above, and quartz below. In many cases ore in the upper levels passes over to gangue in greater depth, an occurrence to be described as primary. Examples of this occur with the copper and

cobalt lodes at Kamsdorf which regularly become poor when leaving the Zechstein formation to enter the Culm where they contain gangue only. The manganese lodes at Ilfeld pass to barite veins in depth while those at Elgersburg similarly often change their manganese content to hæmatite.

In establishing the vertical sequence of primary deposition the figures of output over long years are often useful when care is taken that only those quantities are compared which really do follow one another down along the lode-plane.

When a fissure has been opened more than once it might well happen that the minerals first deposited become supplanted by others and the appearance of primary variation is falsely presented. Bornhardt for instance showed that with the lodes in Siegerland the quartz is younger than the siderite which it has partly replaced. Since the solutions containing the silica came from depth, the deposition of quartz is often most noticeable in depth and when silicification is complete quartz follows siderite like one depth-zone after another though none such exists.

In consequence of the comparatively shallow depth to which mining penetrates it has not yet been possible to evolve regular laws for these variations in primary deposition. It must also be remembered that the surface in any mineral district to-day is considerably lower than that which existed when the lodes were being formed.

Ore-beds on account of their small vertical extent present as a rule but few opportunities for the observance of primary variation in deposition. The difference between the ore carried in the hanging-wall portion of the pyrite bed at Rammelsberg and that of the foot-wall, illustrated in Fig. 164, may however be regarded as primary and probably as resulting from a difference in the composition of the solution.

Secondary depth-zones are those zones formed at different horizons below the surface by subsequent alteration of the material of the primary deposit though otherwise independent of the primary deposition. They consist in the chemical alteration of the upper portion of an ore-deposit to an oxidation zone and to a cementation zone.

Where a deposit of whatever origin comes to the surface it is attacked by the processes of weathering ever active there, the effective agents of decomposition being the oxygen and carbonic acid of the atmosphere and of the surface water, this latter containing various salts and other acids in addition. Some ores, as for instance magnetite, specularite, cassiterite, etc., are extremely resistant; others, particularly the sulphide ores and siderite, readily decompose and their decomposition products in consequence are those most noticed in ore-deposits. In many cases this action of the surface agencies extends deeper than the gossan or oxidation zone, in that the descending solutions deposit again in a

position below the metal which they leached above. Below the oxidation zone therefore, which represents a zone of leaching, another may be recognized in which precipitation occurs. This is termed the cementation zone.

The depth to which the action of the surface agencies extends varies greatly. It depends not only upon the greater or less resistance which the deposit offers to decomposition but also upon the contour of the district and more completely still upon the climate and the level of the ground-water. Above this level a continual movement of air and water takes place and decomposition is consequently greatest there. Since erosion is ever levelling the surface, the products of this decomposition are not always and everywhere retained in position. Should the effect of erosion more than counterbalance that of decomposition the products of the latter are at once removed and the ore-deposit appears at the surface in its original primary condition. If erosion be less rapid than decomposition then in

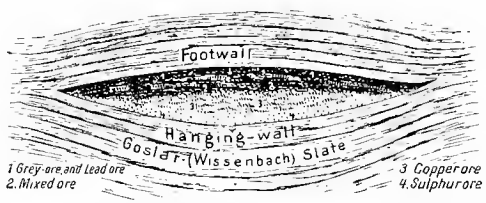

FIG. 164.—Change in the composition of the Rammelsberg ore-bed from the hanging-wall to the foot-wall, considered to be a primary variation.

the case of every deposit readily attacked, a certain depth which has surrendered to the forces of alteration becomes retained as the oxidation and cementation zones.

In regions of intense glaciation any weathered zones previously formed usually become removed by ice movement. In Scandinavia for instance, where during the Diluvial period the surface was worn down by ice, the occurrences of magnetite and hæmatite have a weathered skin often so thin as to be measured in inches, while even the easily decomposable pyrite deposits there have a gossan which where most pronounced is only a few metres deep. The same observations may be made in other districts such as the Pyrenees which have similarly suffered from the action of ice. On the other hand in countries where the climatic conditions favour weathering, deposits generally show well-defined zones of alteration. The pyrite deposits of the south of Spain have a gossan which generally continues 10 m. but often from 15 to 40 m. below the surface, below which again the cementation zone continues for some depth. In Siegerland the siderite lodes are in greater part altered to limonite to a depth of 60 m. and more.

In other countries with deeply-cut valleys and where deposits of iron, copper, lead, etc., occur, the phenomena of alteration are often found to extend in depth even to several hundred metres. Most pronounced examples of deep weathering are afforded by the copper lodes of Butte, Montana, the deposits in Chili, in the Urals, in Arizona, and by the lead-silver deposits of Eureka in Nevada.

The rich ores of the cementation zone are usually present in amount so much the greater as the processes of oxidation and leaching in the upper portions of the deposit were the more intense. From this experience arises the miners' proverb which says 'For a lode nothing is better than that it should have a good iron hat.'

The alterations which bring about the migration of the metal content are in part of a complicated nature. In some cases minerals are pseudomorphically transformed, thus pyrite or siderite into limonite; galena into anglesite, etc. More often however some of their constituents go into solution, chiefly as sulphates, in which condition they become removed to be subsequently deposited at some other place more or less distant. By this removal the gangue usually becomes loose, porous, spongy, or even somewhat brecciated, in a manner to render the subsequent operation of mining considerably more easy. In addition it often happens that it is the less valuable constituents, such as the sulphur with gold lodes, which are thus removed, the original sulphide ores thereby becoming changed to the more easily treated oxides, carbonates, chlorides, etc., or even to the metallic condition. Native gold is accordingly often found in the secondary zones of auriferous deposits whereas in the primary zone it is more often associated with pyrite. With silver- or lead-silver lodes again, the sulphide ores in the primary zone are often so intimately intergrown as to be difficult to treat, whereas the weathered zones on the other hand are found to contain cerargyrite, native silver, cerussite, etc. With many copper deposits the sulphide ores in depth are disseminated throughout a larger amount of pyrite too poor to work, whereas nearer the surface carbonates, oxides, and native copper, occur freed from the iron which in greater part has been removed or re-deposited separately. For zinc ores the occurrence in Upper Silesia where white and red smithsonite in the oxidation zone represent sphalerite in depth, is characteristic. With many of these metasomatic zinc deposits only the oxidation zone is payable, the sulphide ores of the primary zone being too poor to work.

The occurrence of large bodies of ore in the alteration zones of deposits which in the primary zone, in striking contrast thereto, exhibit a disappointingly low metal content, may in many cases only be explained upon the assumption that the metal in those ore-bodies has migrated from a considerable depth of deposit since eroded. Or in other words it may be said

that the descent of the metals in solution on the one hand and the continual removal of the leached portions of a deposit by erosion on the other, may result to-day in the concentration within a small vertical measurement near the surface of considerable quantities of metal which were originally distributed more or less regularly throughout a very considerably greater depth previously existing but now eroded. The zones of alteration may therefore be of great economic importance though in this connection the oxidation zone must be separated from that of cementation. While in the oxidation zone the occurrence of rich pockets of oxide ores is frequent, it is only with the metasomatic lead-zinc deposits that the material of this zone constitutes the chief object of mining. The exploitation of the cementation zone however frequently of itself constitutes a profitable undertaking. The famous old rich silver deposits of Potosi, Oruro, etc., in Bolivia; of Pasco in Peru; Chanarcillo, etc., in Chili; the deposits of Guanajuaro, Zacatecas, etc., in Mexico; of Broken Hill in New South Wales; the copper-silver deposits of Butte, in Montana; the copper deposits of Arizona and of the Urals, all owe their importance in greater part to accumulations of ore in the zones of alteration.

In the following paragraphs different cases of alteration are discussed.

Siderite changes sometimes to limonite when a diminution of volume to the extent of 19·5 per cent takes place, and sometimes to hæmatite. It is however worthy of remark that pseudomorphs of these two minerals after siderite, which show no sign of diminution in volume, have often been found at Bilbao, Siegen, and elsewhere. At other places siderite becomes dissolved by carbonic acid in solution, the iron becoming afterwards precipitated either by oxidation or by the escape of free carbonic acid. In this way limonite may be deposited in one place and manganese ore in another, though in the original siderite both metals were in the closest association. Clean manganese-iron ore may therefore often be present in the gossan of such deposits though the original siderite may only have contained 5-7 per cent of manganese. Solution and subsequent precipitation of iron in this manner gives rise to drusy cavities and stalactites of limonite, such ore in consequence often showing a reniform structure, that is one of concentric shells with an internal radial structure.

Pyrite upon decomposition generally forms limonite or some other iron ore, but sometimes ferric sulphate which passing into solution exerts in its turn a solvent action upon many sulphide ores and particularly those of copper: ferric sulphate, as previously mentioned in the chapter on mineral formation, also dissolves native silver and gold. In this way in the huge pyrite deposits of the south of Spain the copper near the surface together with the accompanying small amount of gold and silver became

leached and, after a descent during which any remaining oxygen was consumed, deposited again at the contact of the gossan and the pyrite beneath, as the result of the reducing effect of that pyrite. This occurrence is illustrated in Fig. 12. In the lower portions of the gossan of these deposits native sulphur is also occasionally found, its presence being explained by the formula: $Fe_2(SO_4)_3 + CuS = 2FeSO_4 + CuSO_4 + S$. Below the gossan, copper both from the gossan as well as from the portion of the original deposit which has been eroded, becomes deposited in the zone of cementation which is therefore always the richest portion of these deposits. The decrease in the copper content which is noticeable at depths of 150–300 m. or well under the ground-water level, is however probably rightly regarded as primary in character.

With the copper deposits of Butte in Montana, which are quartz lodes carrying argentiferous pyrite and chalcopyrite as the primary ores, the copper in greater part is leached from the outcrop down to a depth of 100 m. more or less, so that these lodes at first were worked for silver. Afterwards below this zone very rich copper ore consisting chiefly of chalcocite and bornite was found, in which the copper leached from the silver zone above was to a great extent concentrated. Such an occurrence is termed by American investigators 'sulphidic enrichment.' Primary ore in these lodes at Butte was first encountered below and often considerably below the ground-water level, an appearance probably consequent upon subsequent tectonic alteration of that level.

At Ducktown in Tennessee, where the primary ore is pyrrhotite, a typical gossan is found near the surface. Below this however, very rich copper ore consisting chiefly of chalcocite and cuprite occurs forming an enriched zone which contains not only the primary copper but also much of that leached from the upper portions of the deposit.

Where solutions containing carbonic acid are in active circulation or where limestone or dolomite form the country-rock, azurite, malachite, cuprite, tenorite, chrysocolla, etc., occur in considerable amount as the products of the alteration of copper deposits, as for instance in Arizona, in the Urals, at Chessy near Lyon, and at Burra Burra in South Australia.

With the tin-copper lodes of Cornwall also, the copper is in greater part leached from the gossan. In the primary ore, immediately below this, copper ores occur with but little tin, and then again in greater depth, and as a part of the primary deposition, tin ores with but little copper. In working these lodes three stages have consequently been noted: the first during which the mines were worked for the iron and tin in the gossan; the second when the mines were worked almost entirely for copper; and the third when in greater depth tin almost exclusively was produced.

The tin lodes at Mount Bischoff in Tasmania were also capped by a gossan which was there spoken of as the ' Brown Face ' (Fig. 165).

The tin of the tin-silver lodes of Bolivia, in so far as it exists as cassiterite, suffers no removal during decomposition of the lodes near the

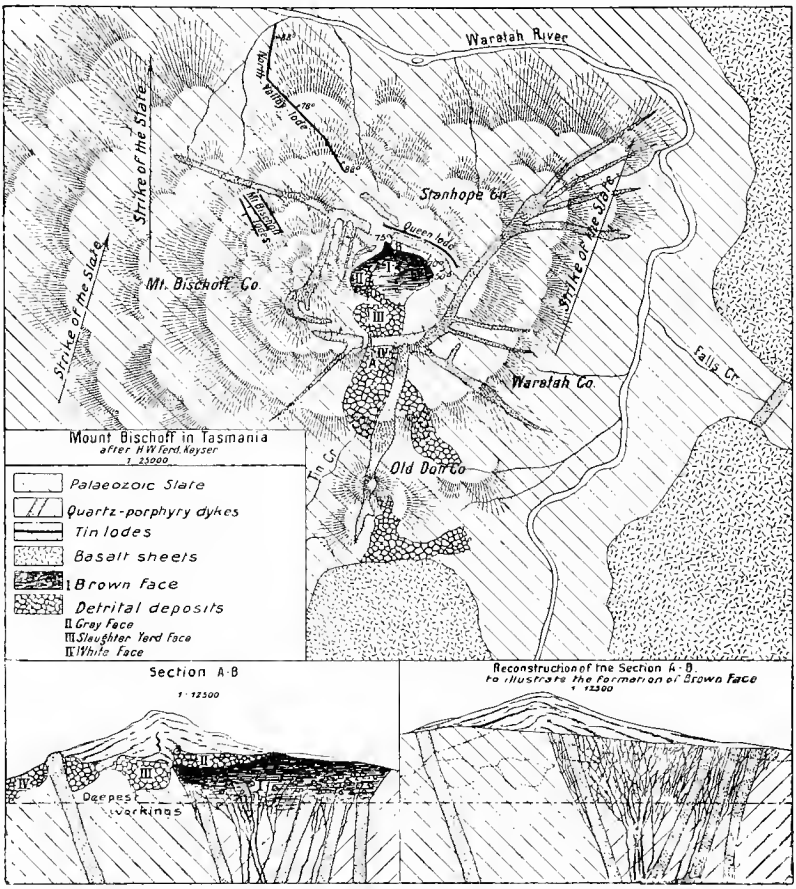

FIG. 165.—Gossan formation with the tin lodes at Mount Bischoff. The so-called Brown Face.

surface; that however which occurs in stannine goes, together with the silver, to enrich the cementation zone, while the iron of the pyrite is removed. According to Stelzner[1] the so-called wood-tin, which hitherto has only been met in the upper levels of tin lodes in Cornwall, Bolivia, etc., and in gravel-deposits, is a decomposition product from stanniferous pyrite and stannine.

[1] *Zeit. f. prakt. Geol.*, 1897.

Galena in weathering generally becomes altered to the sulphate, anglesite, though when carbonic acid is present the difficultly soluble carbonate, cerussite, is formed. Pyromorphite the phosphate and mimetite the arsenate occur less frequently.

Sphalerite weathers chiefly to the carbonate, smithsonite, and less frequently to the hydrous carbonate, hydrozincite, or the silicates, hemimorphite and willemite. Such a change as was mentioned on p. 214 is in fact an enrichment so that with metasomatic lead-zinc deposits the oxidation zone may be payable though the primary zone may have but a low metal content. Any pyrite present becomes changed at the same time to limontite.

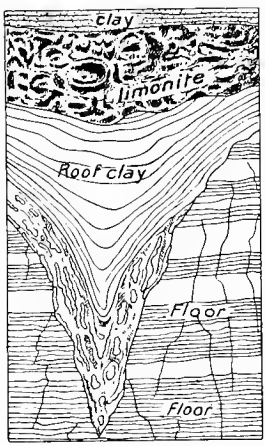

FIG. 166.—Secondary alteration of pyrite to limonite. The clay represents the alumina content of the impure limestone. Illustration taken from the zinc deposits of Upper Silesia.

The decomposition of arsenic ores generally produces arsenates, such for instance as erythrite from smaltite; annabergite from chloanthite; and in addition arsenolite from realgar and orpiment. Those arsenic ores however which are associated with a considerable iron content become decomposed in a manner similar to pyrite; the iron becomes separated as oxide or hydrate while the arsenic and sulphur are in greater part removed. If gold be associated with arsenopyrite, as at Hussdorf in Silesia, this becomes leached from the oxidation zone to be deposited in the cementation zone beneath, below which again the primary ore poor in gold is found. From the sulphide antimony ores sometimes antimonates are formed and sometimes valentinite, senarmontite and pyrostibite. Compounds of bismuth, wolfram, vanadium, chromium, and molybdenum, are less often found in the gossan, though the lead-wolframate, stolzite; the lead-chromate, crocoisite; and the lead-molybdate, wulfenite, perhaps deserve mention. The sulphates, chlorides, etc., are also not of common occurrence. If in addition it be added that where the original minerals or the surface waters contained but a small amount of phosphoric acid or uranium, the phosphates and uranates of the heavy metals, as for instance pyromorphite, kakoxen, uranium-ochre, and uranium-mica are formed, it becomes evident that the gossan or oxidation zone of ore-deposits contains a greater variety of minerals than the other zones.

The plentiful occurrence of the chloride, bromide, and iodide of silver as well as metallic silver in the many famous silver deposits in Chili, Bolivia, Peru, Mexico, and in the desert regions of the Rocky Mountains

and of the Sierra Nevada, as well as in many cases in Australia, has been attributed by some authorities [1] to the entry of sea-water along fissures and lodes. In support of this view it is quoted that at Chanarcillo the relative proportions of chlorine, bromine, and iodine in the lodes is the same as that obtaining in sea-water. Against this however Penrose [2] mentions the fact that in almost all the above cases the outcrops are in the neighbourhood of saline lakes or marshes and that these halogens are consequently derived from surface salts. He refers also to the occurrence of the basic copper chloride, atacamite, at the outcrop of the sulphide copper lodes in the Atacama desert. The small amount of silver chloride occurring as cerargyrite in the upper portions of the European silver lodes, at Freiberg, Johanngeorgenstadt, Kongsberg, etc., is sufficiently explained by the sodium chloride in the ordinary drainage water. In places elsewhere large accumulations of the chloride, such for instance as those at Broken Hill, may also be explained in this manner. Apart from the totally different character of the ores in the deposits just mentioned these occurrences differ also from those on the west coast of South America in that they are unaccompanied by the corresponding compounds with bromine and iodine. Of these silver ores in Bolivia, varieties termed pacos, mulattos, and negrillos, are differentiated. The first are the greatly decomposed and partly chloridized oxidation ores which occur in great quantity in the deposits of Potosi, Oruro, etc.; the last are the dark undecomposed sulphides from depth; while the mulattos represent the ores intermediate between those two.

With auriferous deposits the phenomena of decomposition are particularly important. Where telluride gold ores exist in depth, weathering when given full play so effects their destruction that near the surface only metallic gold appears. This is the case in Western Australia, Cripple Creek, and in occurrences in the Rocky Mountains. The tellurium is usually completely removed or retained only to a small extent in such secondary minerals as tellurite TeO_2, durdenite $Fe(TeO_3)_3 + 4H_2OnTeO_2$, ferro-tellurite, and magnolite Hg_2TeO_4, etc. The tellurides apparently are readily decomposed. In those districts therefore where they come undecomposed to the surface, as at Nagyag in the Siebenbürgen, at Hauraki in New Zealand, etc., it is probably the case that the oxidation zone within recent geological time has been eroded. The particularly remarkable fact that, with these auriferous telluride deposits, there is no enrichment in the zone of cementation is discussed later in the chapter dealing with those lodes.

[1] Moesta, *Ueber das Vorkommen der Chlor-, Brom-, und Jodverbindungen besonders in Chili.*

[2] 'The Superficial of the Ore-Deposits,' *Journ. of Geol.* II., 1894.

With the ordinary sulphide gold deposits—these being those quartz lodes or beds where in the primary ore the gold is almost exclusively associated with sulphides—the gold occurs in the gossan in the free state, constituting what is known as free-milling ore, that is to say, ore from which the gold can be won by simple amalgamation. Below this zone, which in consequence of leaching is generally poorer than the primary zone, there is a zone of enrichment in which the gold leached from the portion of the deposit still existing above as well as from that long since eroded, becomes precipitated by the primary undecomposed sulphides. The native gold of crystalline character found plentifully in isolated places upon the Witwatersrand was doubtless formed in this manner. J. R. Don also explains the frequent occurrence of large masses of metallic gold in the upper portions of many Australian lodes in this manner. It is worthy of note that such re-deposited gold contains less silver than the gold from the primary ore. In rare cases a relative enrichment in the oxidation zone may occur by the decomposition and removal of the pyrite without the concomitant solution of the gold.

From these considerations of the secondary depth-zones the following generalization may be made. Where deposits of whatever genesis come to the surface atmospheric waters penetrating into them produce by their power of solution some migration of the metal content. The metals go into solution chiefly as carbonates, sulphates, and chlorides, and while some of them in this manner become transferred to greater depth, others immediately become precipitated near the surface forming there the ores characteristic of the oxidation zone. Almost all ore-deposits contain iron in considerable amount as pyrite, and as iron in the presence of oxygen is difficult to keep in solution, this metal becomes precipitated more quickly than most of the others. An enrichment of iron therefore takes place in many cases at the surface, sometimes to such an extent that the occurrence is termed the iron cap or gossan of the deposit. Even where the amount of iron so precipitated is small its brown colour is always plainly to be seen in the fractures and cracks where oxidation has been active.

That portion of the heavy metals which does not thus become fixed in the oxidation zone descends in solution till it is precipitated by the reducing effect of the primary sulphides in the cementation zone, either in the metallic form or in that of rich sulphides ; those metals which have little affinity for oxygen, such as gold, silver, copper, etc., become precipitated in metallic form while among the sulphides those of copper and silver are the more important. In this cementation zone not only may the metal which was formerly in the oxidation zone be concentrated but also that which existed in that larger portion of the deposit which since it

was first formed has surrendered to erosion. On account of their richness the ores which characterize this zone are very important. They have already been given in the chapter on ores. Below this cementation zone follows the primary zone. These three zones, oxidation, cementation, and primary deposition, contain ores so different in character and metal content and so various in amount that each demands a separate investigation and a separate estimation of the metal quantities.

The lower limit to the alteration zones may vary but where the phenomena of decomposition by surface agencies are simple and complete it stops at the ground-water level. These phenomena are not of necessity present with every ore-deposit. They demand not only a certain minimum of rainfall but also a certain relation of erosion to the advance of the chemical-geological changes. When for instance erosion proceeds more energetically than chemical alteration no alteration zone remains to mark the latter. This is the case when the rocks are young and disintegration easy; under such conditions the ore-deposit may appear at the surface in its primary condition. When on the other hand erosion lags behind, then a complete profile of the oxidation and cementation zones may remain above the primary ore or at least some portion of the cementation zone will be present.

INDICATIONS OF ORE-DEPOSITS AT THE SURFACE

1. *Ridges.*—The difference in hardness between the material of a deposit and the country-rock has at times much to do with the expression of a deposit at the surface. When the deposit as often happens consists chiefly of quartz, it is generally harder than the neighbouring rock so that in consequence it forms a more or less pronounced wall or ridge. Laterite and surface detritus not only tend to hide such ridges but when they occur to any extent they protect the deposit from further destruction. Should the ore-deposit be softer than the country-rock or should it on account of shattering be less resistant to erosion, the course of such a deposit becomes marked on the surface by a furrow, on either side of which the country-rock forms a ridge. The most unfavourable case is when the deposit and the country-rock have approximately the same hardness, when no indication based on prominence or depression can exist. Most of the young gold-silver lodes and those sulphide lead-zinc deposits. which form composite lodes in slate country, are thus circumstanced.

2. *Colouring.*—The oxide compounds, particularly of many heavy metals such as those of iron, copper, and nickel, possess striking colours. Many ores contain iron either as a principal constituent as in pyrite, or accessory as in galena and sphalerite. The effect of surface agencies upon such ores is to produce ferric hydrate or ferric oxide, so that at the surface the ore may be changed into a highly ferruginous mass, the gossan, distinguishable from the country-rock by its brown or red colour.

Should the primary deposit contain sulph-arsenical cobalt and nickel ores, these by weathering become altered to the more simple arsenides which are distinguished by their red and green colour respectively. If copper be contained, then the green carbonate, malachite, the blue carbonate, azurite, or the blue-green silicate, chrysocolla, may be formed. With many deposits also, the colour of the ores themselves is noticeably different from that of the country-rock. Metasomatic deposits of limonite and bauxite in limestone areas may be recognized by their colour, even at a distance, when the vegetation is not too thick.

3. *Attendant Faulting.*—In those frequent cases where an ore-deposit is at the same time a fault causing a lateral dislocation of the beds present, the course of the deposit may be determined without the help of any other indication by plotting those beds which are easily distinguishable either by their petrographical characteristics or by the fossils they contain. A reliable topographical map or sketch is necessary and the object in view must be realized when the plotting is being made. This plotting method is particularly valuable in those cases where the lodes carry ore only in depth. The sulph-arsenical nickel-cobalt lodes in the Zechstein contain nickel and cobalt ores chiefly between the two terminals of the *Kupferschiefer* which they displace. Where the surface is occupied by younger Zechstein or perhaps even by Trias no indication of ore may be observed, where these lodes outcrop and the colours associated with nickel and cobalt are entirely wanting; the course of the lode may nevertheless be determined by careful plotting.

4. *Springs.*—All deposits, and especially those which at the same time are accompanied by faulting, form excellent channels for the circulation of underground and spring water. In consequence springs and water-issues in many cases are good pointers to follow when prospecting. Moist spots covered with bright-green vegetation on a slope otherwise dry deserve close examinatiou, especially if they are seen to maintain a good line. Such occurrences may be observed at the outcrop of many of the lodes in the Harz.

5. *Plants.*—Some plants need certain metal-salts for their proper growth and development; others when they take up certain salts show characteristic changes in leaf and flower. These facts may in suitable circumstances be found of use in picking up the course of a lode. The violet, *Viola Lutea var. Calaminaria* which grows upon zinc deposits; the butterfly flower, *Amorpha Canescens Nutt.*, which grows on clayey plumbiferous soil in Missouri; and a clove, *Polycarpaca Spirostylis* by name, which grows on cupriferous soil in Queensland and the ashes of which contain copper, are examples of this peculiarity. Other influences which lodes in their course apparently have upon vegetation may be ascribed in greater part to the nature of the water carried in the fissure or to the poverty of the lode material in nourishment for plants.

6. *Fragments of Ore in the Surface Detritus.*—Fragments of ore and of lode material are generally found along most deposits. A lode with greater hardness than the enclosing rock gradually forms a projecting wall which eventually breaks, distributing its fragments within a long narrow width along its course. This occurrence could be seen a few years ago with many lodes in the neighbourhood of Felsöbanya in Hungary, and with the deposits of lead ore at Ziegenhals in the Taunus. Such fragments

are generally arranged as a zone parallel to the strike of the lode and chiefly on the foot-wall side. A prospecting trench made at right angles to this direction and, when the dip of the lode is not known, continued far enough on each side, will generally result in the discovery of the deposit.

Such fragments may be carried by streams or landslides down to the valleys, there to undergo concentration by water. When seeking the deposit from which such fragments came, it must be kept in mind that this must lie upstream from or above the highest point of discovery of the pieces. Similarly, if fragments or pieces are found in the surface detritus upon a slope, the deposit from which they were derived must also be sought above the place where they were found. If fragments of a deposit occur scattered in laterite it may be reckoned with fair certainty that the original deposit is not far distant, since the rock pieces found in laterite come in greater part from the country in the immediate neighbourhood. Cases occur, though less frequently, where the easily decomposed and easily transported constituents of a deposit, generally the non-metallic portions, have been removed while the heavy constituents have settled down upon the original deposit.

7. *Magnetism of the Minerals.*—The magnetic properties of certain minerals sometimes provide a valuable means of tracing and following deposits not yet completely developed. This method of search is termed magnetic prospecting, the principle of which is based upon the determination of the amount of deviation which a magnetic needle undergoes at different distances from a deposit or in response to deposits of different mass. The measure of this deviation serves not only to indicate the presence of a deposit but gives also a good idea of its disposition and size. Naturally only such ores can in this manner be demonstrated to be present as exert a considerable influence upon the magnetic needle, and in consequence magnetic prospecting finds its greatest application with iron ores and especially with magnetite.

The most simple instrument to use in such prospecting is the ordinary miner's compass so arranged that it may not only swing horizontally but vertically. The area to be prospected is then laid out in small squares marked at the corners by wooden pegs. The amount of deviation is observed at each of these corners and entered upon a plan till finally in this way zones of greater, medium, and less deviation, become determined. For more exact investigation the instrument known as the Tiberg clinometer is used. With this instrument the magnetism of the earth both in its vertical and horizontal components is eliminated so that any inclination of the magnetic needle is caused solely by the vertical component of the deposit's magnetism. To determine the horizontal component the magnetic corrector of Thaléns is employed. These methods which originated in

Sweden have been employed both in that country and in Norway with excellent results in the investigation of magnetic deposits, particularly those rich in magnetite.

The electric properties of deposits may also be used in prospecting on the surface. Since generally speaking the material of a deposit differs more or less in composition from that of the country-rock, an ore-deposit offers either resistance or conductivity to the electric currents streaming within the earth's mass at that point. Most ores are better conductors than the rocks enclosing them and the changing intensity in the ticking of an induction apparatus, the current of which is led to earth, may therefore be of service in the search for deposits; the ticking is louder the greater the resistance. Since however the material of an ore-deposit can only make itself felt as a greater or as a lesser resistance, and this resistance is only indirectly dependent upon the presence of ore, this property of an ore-deposit can but seldom be of much service in prospecting. A fissure filled with water or a bed differing materially from the others among which it lies would indeed produce the same effect. From experience hitherto it may therefore be said that the electrical conductivity of an ore-deposit can only come into question in prospecting when such a deposit occurs regularly in a formation from which both petrographically and with respect to its chemical-physical properties, it differs materially.

8. *Old Workings.*—In all large mining regions which have been known and worked for ages several distinct periods may generally be recognized. During the earliest the gossan ores and those of the cementation zone were won, as far as the primitive means and the arts of mining and metallurgy then allowed. Work then was generally stopped at ground-water level, till later an advance in mining technology allowed a second attack to be made upon that deeper portion for which the new equipment was adequate. These old workings now make themselves evident on surface chiefly as subsidences produced either by the collapse of old shafts or air-holes, or by that of old stopes.

A careful survey of these will in most cases give a good idea of the extent of the deposit beneath and at the same time of the disturbances to which it has been subjected. With undisturbed occurrences, whether lode or bed, and with regular distribution of the metal content, the old workings form a long unbroken series. Where on the other hand a deposit is interrupted by transverse faults the resultant lateral dislocations are also disclosed by the broken line of these old workings. If faults were numerous, or if the distribution of the ore were so irregular that the ancients mined the better parts only, the disposition of the old workings on surface would reproduce the same lack of regularity.

Since the ancients, in consequence of the much higher prices formerly ruling for the noble metals, searched the surface most completely, the old workings, especially in cases of large lateral dislocation of important deposits, are a very important and reliable guide when searching for the continuation of an occurrence.

THE SCIENTIFIC CLASSIFICATION OF ORE-DEPOSITS

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THE classification of ore-deposits has hitherto been based upon most varied principles, namely:

1. Upon morphology, that is form, outline, or extension.
2. Upon content, on the basis of the characteristic constituent.
3. Upon genesis, according to the views of genesis held at the time.

The purely empirical classification based upon morphology is simple for the practical miner who arranges his method of working upon the same basis. This system in consequence is much advocated even to-day in text-books on mining; for instance by Callon, Neve Foster, Lottner-Serlo, Köhler, etc. Scientifically however it cannot be defended because it lays the greatest importance upon but the external properties of a deposit. The classification according to content, giving prominence to the most important metal present, economically speaking, is in many senses a good arrangement, especially from the point of view of metallurgy and political economy; it however takes no account of the geological position of the deposit. A classification based entirely upon genesis is without doubt the most scientific and the best principled. It encounters however even to-day great difficulty in that the origin of many deposits remains completely obscure. Before giving the classification which the authors consider embraces all the present-known circumstances and properties of deposits, and in order to provide a basis for the more detailed treatment of the subject, an historical review of the subject is first given.

Attempts at classification are to be found in the very oldest text-books on mining and geology. These attempts however varied they might be, almost all put forward a grouping in which morphology alone was considered. Werner in 1791 exceptionally divided the ore-deposits into (*a*) those contemporaneous with the country-rock, and (*b*) those formed later, providing thereby the first classification based on genetic principles. The first independent course upon the study of deposits originated with Waldauf von Waldenstein in 1824 who, following the view of his time, differentiated between regular and irregular deposits. In greater detail regular deposits consisted of tabular beds and lodes, while irregular deposits included masses and deposits where the ore occurred in separate scattered bodies of considerable dimension.

Burat in 1846, G. A. von Weissenbach in 1850, and Whitney in 1854,

put forward classifications based partly upon morphology and partly upon genesis. Burat in his main grouping differentiated regular deposits and included therein lodes, masses, and stockworks. Lodes he described most completely as indeed did all the early investigators, moved thereto by the work of Werner. While in this and in his main grouping he followed the tendency of the time, in a supplementary chapter upon deductions concerning the theory and exploitation of ore-deposits he gave a classification which showed that he was far ahead of his colleagues. In this he took into consideration the more or less close relationship between ore-deposits and eruptive magma, and differentiated :

1. Eruptive deposits and tin occurrences.
2. Contact-deposits.
3. Metamorphic deposits.
4. Lodes.

His metamorphic deposits were those into which metallic substances penetrated subsequently and which were not in immediate relation to eruptive rock. The *Kupferschiefer* was for instance reckoned among them, representing that group of metamorphic deposits which constituted a connecting link with those other deposits contemporaneous with the rocks enclosing them. A difference was made between a contemporaneous metamorphism taking place when the rock and ore were formed, and metamorphic deposits of later formation. The first correspond to the sedimentary beds of to-day, the latter to the metasomatic deposits.

B. von Cotta in his famous *Lehre von den Lagerstätten*, Part I., 1859, followed a purely morphological grouping. He differentiated between regularly-shaped deposits, such as beds and lodes, and those irregularly shaped such as masses and impregnated zones. In addition he grouped the deposits according to the characteristic mineral contained ; and finally, in the second portion of the work, he arranged and described the deposits under their geographical distribution. In the preface to the second edition, wherein the principal conclusions are reviewed, he divided the different occurrences into :

I. Regular :	II. Irregular :
(*a*) Beds.	(*a*) Masses.
(*b*) Lodes.	(*b*) Impregnated zones.

The true beds according to Cotta were formed by deposition from water, though subsequently they might have been altered. As true lodes he included not only those occurrences of precipitation from aqueous solution, but also individual cases of sublimation and molten injection. The masses might be irregular beds or lodes, but also other irregular deposits

occupying space opened by volcanic activity. The scientifically-speaking far-advanced genetic classification of Burat was, it is strange to say, not made use of by Cotta. It is true that in comparison with the main grouping of Burat that of Cotta marked an advance in one particular, namely, that in his classification the beds were given a definite and independent place whereas with Burat their position was indeterminate. Against this however Cotta gave magmatic segregations and contact-metamorphic deposits no separate place. He acknowledged, it is true, that deposits did occur within or as contact-formations attendant upon eruptive rocks, and recognized that these represented the concentration of mineral matter originally regularly distributed in the earth's mass, but he put no value upon grouping the deposits in harmony with these genetic considerations. Impregnated zones were divided into independent and dependent. The first, occurring bed-like or in the form of masses, contained ore formed at the same time as the rock itself. The latter occurred as border zones and beds, lodes and masses, and were neither contemporaneous with the principal deposit nor were they formed by its decomposition. Cotta himself pointed out that his class of independent contemporaneous impregnated deposits were not impregnations in a scientific sense.

J. Grimm in 1869 followed in general the morphological lines of Cotta, his classification being :

I. Primary constituents of, or inclusions in, the rock :
   (*a*) Original dissemination or impregnation.
   (*b*) Secondary dissemination.
II. Separate deposits or subordinate rock members :
   (*a*) Tabular masses.
   (*b*) Masses, regular and irregular, and stockworks.

In this classification the factor of genesis received no consideration. In the group of original disseminations small magmatic segregations as well as subsequent impregnations were included. The secondary disseminations consisted only of gravel-deposits and ore-bearing detritus. The tin lodes of Zinnwald, which at that time were properly and almost universally classed as true lodes, he classed with beds and seams because they passed from the zone of greisen out into the country-rock.

Callon in 1866, Lottner-Serlo in 1869, Neve Foster in 1894, and Köhler in 1903, developed systems approaching that of Grimm. In addition to these authors who together with Burat regarded the deposits entirely from the view of morphology, there were others who took genesis also into consideration. Naumann, from 1866 to 1872, made the first endeavour in this direction in his work *Geognosie*, where he treated the

ores as subordinate rock-forming minerals and classified the ore-deposits as follows :

1. Ore-bearing layers, including fahlbands, impregnated zones, etc.
2. Gravel-deposits.
3. Ore-beds in the narrow sense, including beds and bedded masses.
4. Lodes.
5. Eruptive deposits.

The first class corresponds in its scope to the ' original disseminations ' of Grimm, though the change of name is a decided improvement. Naumann explains that this class included deposits of very different genesis, and that to it belonged the so-called half-formed beds, or those occurrences which differing from ordinary beds only in the smaller size of the ore-body, occasionally pass over to become beds proper. The separation of the first three groups on an equal footing with the others cannot be maintained. Metasomatic deposits are placed with the ore-beds which is not correct ; while the contact-deposits receive no mention at all.

The classification of Whitney in 1866 resembled that of Naumann. He differentiated deposits into superficial, stratified, and unstratified, as the main groups, while in the subsidiary groups he gave some consideration to genesis. Phillips and Louis in 1896, using the same main divisions as Whitney, completed their classification as follows :

I. Superficial deposits, formed by :
   (*a*) The mechanical action of water.
   (*b*) Chemical action.

II. Stratified deposits, formed by :
   (*a*) Precipitation from aqueous solution.
   (*b*) Precipitation from aqueous solution, but subsequently altered.
   (*c*) Precipitation from impregnating solutions.

III. Unstratified, such as :
   (*a*) True veins.[1]
   (*b*) Segregated veins.
   (*c*) Gash veins.
   (*d*) Impregnations.
   (*e*) Stockworks.
   (*f*) Fahlbands.
   (*g*) Contact-deposits.
   (*h*) Chambers or pockets.

The deposits under II. (*b*) are generally those of hæmatite and magnetite occurring in highly altered rocks of Cambrian, Silurian, Devonian,

[1] Lodes.

or Carboniferous age. The author assumes that these occurrences were originally precipitated as ferric hydrate which later, by metamorphism of one nature or another, became changed to their present condition. To II. (*c*) such deposits as the *Kupferschiefer* belong, the author considering this to have been formed by the saturation of a particular stratum with mineral solutions from which the ore from one cause or another became precipitated. For such deposits as for instance the bed of iron ore in the Senon at Peine, which after formation by the mechanical action of water became covered by younger beds, no subdivision under stratified deposits has been provided. On the other hand in II. (*a*) the author placed a number of metasomatic deposits. With contact-deposits also he reckoned not only the contact-metamorphic deposits but also those which without reference to their genesis are found where two different rocks came into contact. In general however the subdivisions are based upon genesis. Superficial deposits for instance are divided according as to whether they were formed by mechanical or by chemical action.

Von Groddeck in 1879 was the first author to refuse form and to accept genesis exclusively as the basis for his classification. He differentiated:

A. Original deposits:
   1. Stratified deposits.
   2. Massive deposits.
   3. Cavity-fillings.
   4. Metamorphic deposits.

B. Detrital deposits.

This grouping however separates the detrital deposits from the stratified deposits from which however they differ only in age. Groddeck himself later[1] admitted the force of this and withdrew the group of detrital deposits. The names given to the first two classes in addition to their relation to genesis are also indicative of form which indeed is a function of genesis. The contact-deposits, which in a special section the author places in part with the ore-beds and in part with the metasomatic deposits, are not separated as a class. The stratified deposits of Groddeck are those formed originally on the surface by gradual deposition from water in just the same manner as the non-metalliferous sediments; they have in consequence the same strike and dip as these sediments and occur either as surface or as interbedded deposits. By massive deposits Groddeck meant crystalline rocks of molten origin. The cavity-fillings constitute that general group formed later than the country-rock, these according to their form being subdivided by Groddeck into lodes and chamber-fillings.

Stelzner, in a critical review of Groddeck's classification,[2] raised the

[1] *Berg- und huttenm. Zeit.*, 1885.

[2] *N. J. f. M.*, 1880, II.

point that in the class of metamorphic deposits, occurrences of very different genesis are put together, namely :

(*a*) Metasomatic lead-, zinc-, and iron-manganese deposits.
(*b*) Contact-deposits proper, the products of contact metamorphism.
(*c*) Various other deposits resulting from metamorphism, such for instance as the occurrence of greisen with tin deposits.

He proposed therefore that the metasomatic deposits should be placed in a class by themselves, with which proposal Groddeck appeared agreeable, though he called attention to the close connection between the lodes and these metasomatic occurrences.

The classification put forward by J. F. Kemp in 1892, 1895, and at times between 1900 and 1907, is also purely genetic, and as follows :

I. Magmatic segregations.
II. Deposits chemically deposited from solution :
  (*a*) Precipitation on the surface.
  (*b*) Impregnation.
  (*c*) Filling of fractures arising from cooling or drying.
  (*d*) Chamber-deposits in limestone.
  (*e*) Filling of fractures in shattered and broken strata.
  (*f*) Filling of openings in anticlines and synclines, often connected with metasomatis.
  (*g*) Crushed zones accompanying fissures or faults.
  (*h*) True fissure veins.[1]
  (*i*) Segregations in volcanic necks.
  (*k*) Deposits in connection with eruptive rocks.
  (*l*) Deposits formed at the alteration of eruptive rocks.
III. Deposits formed by the mechanical action of water :
  (*a*) Detrital deposits :
    1. Superficial.
    2. Covered.
  (*b*) Eluvial gravels.

The several subdivisions of group II. do not indicate uniformity in the point of view throughout. The author appears sometimes to have considered form and at other times genesis. Lodes and cavity-fillings so closely allied in genesis, account for no less than six subdivisions, (*c-h*), wherein sometimes the form of the fissure or cavity and sometimes its origin play the greater part. The three main divisions are also of very unequal compass. Since most ores result by chemical precipitation from aqueous solution this group is much the greatest, an admission which Kemp makes by providing it with eleven subdivisions. Since also mineral

[1] Simple lodes.

solutions must have been active to a greater or less extent with all the various geological processes, deposits of most varied character must be embraced by this group, lodes becoming classed with contact-deposits, and these again with such occurrences as are formed by the migration and deformation often taking place at rock alteration.

In the year 1893 Posepny put forward the following genetic classification :

I. Deposits in spaces of discission :
  (*a*) Lodes in stratified rocks and with no connection with eruptive rocks.
  (*b*) Lodes in the neighbourhood of eruptive intrusions.
  (*c*) Lodes within extensive complexes of eruptive rock.
II. Deposits in spaces formed by the solution of material ; or deposits in soluble rocks :
  (*a*) In disturbed country.
  (*b*) In undisturbed country.
III. Metamorphic deposits :
  (*a*) In distinctly stratified rocks.
  (*b*) In soluble rocks.
  (*c*) In crystalline schists and eruptive rocks.
IV. Hysteromorphic deposits :
  (*a*) Due to chemical influences at the present surface.
  (*b*) Due to mechanical action at the present surface.
  (*c*) Due to the hysteromorphic occurrence of older geological formations.

The fillings in spaces of discission, or spaces following upon rupture, are the lodes proper ; and the hysteromorphic deposits are those formed chemically at the surface whether in older or younger geological epochs.

Fuchs and de Launay in 1893 regarded the ore-deposits from the point of view of the metals they contained, and arranged the deposits of each metal or element according to a geological system. In a theoretical treatise appearing at the same time as the principal work, de Launay differentiated :

I. Deposits included in eruptive rocks.
II. Lodes.
III. Sedimentary deposits.

To the first group belong principally the magmatic segregations but also other occurrences within eruptive rocks such as the garnierite veins, the copper deposits of Lake Superior, and several endomorphic contact occurrences such as tin ore in greisen. The genetic principle is there-

fore not entirely maintained in this classification, and as with other French authorities the sedimentary deposits receive little consideration.

A similar classification was that put forward by Höfer in 1897 wherein the principal groups are differentiated according to their age-relation with the country-rock; the subsidiary groups according to genesis; and finally the classes according to size and form. According to genesis Höfer, speaking generally, differentiated sedimentary deposits, eruptive deposits, cavity-fillings, and metamorphic deposits. His complete classification was as follows, each subsidiary group being further divided according to size and form:

I. Contemporaneous with the country-rock:
  Sedimentary deposits.
  Eruptive deposits.
II. Younger than the country-rock:
  Cavity-fillings.
  Metamorphic deposits.

Stelzner[1] gave in his lectures the following classification:

I. Protogene deposits:
  A. Syngenetic:
    Eruptive.
    Sedimentary.
  B. Epigenetic:
    Hypostatic:
      1. Fissure-filling.
      2. Cavity-filling.
    Metasomatic.
II. Deuterogene deposits:
  A. Metathetic.
  B. Gravels, or mechanical deposits.

Gürich in his critical description raises doubts as to the propriety of this division into protogene and deuterogene deposits, because strictly speaking in all chemical-geological phenomena there is no actual accretion of new material but only a new arrangement of that already present from the beginning, and consequently no proper test for protogene deposits can exist. He therefore proposed:

I. Impregnation deposits:
  (*a*) Syngenetic.
  (*b*) Epigenetic.
  (*c*) Metagenetic.

[1] Gürich, *Zeit. f. prakt. Geol.*, 1899, p. 175.

II. Magmatic or solidification deposits :
  (*a*) Syngenetic.
  (*b*) Epigenetic.
  (*c*) Metagenetic.
III. Precipitation deposits :
  (*a*) Syngenetic.
  (*b*) Diagenetic.
  (*c*) Metagenetic.
IV. Concentration deposits :
  (*a*) Residual deposits.
  (*b*) Gravel deposits.

It must be acknowledged that this classification of Gürich practically covers all the cases which could arise in the formation of ore-deposits and therefore deserves great consideration. Unfortunately however it is practically impossible to arrange all the known occurrences according to it. In many cases for instance it is not possible to maintain a separation between formation by sublimation and that by precipitation since in many phenomena of precipitation vapours play an important part.

In numerous essays published by Vogt discussing genesis much is found of considerable value relative to the classification of deposits. In that cited at the beginning of this chapter Vogt proposed the following grouping for those deposits due in any way to eruptive phenomena :

I. Products of magmatic differentiation :
  1. Segregations of oxide ore.
  2. Segregations of sulphide ore.
  3. Segregations of metal.
II. Products of pneumatolysis and pneumatohydatogenesis :
  1. Contact-metamorphic deposits.
  2. Cassiterite lodes.
  3. Apatite lodes.
  4. Pegmatite lodes containing zircon-, boron-, and fluorine minerals, etc.
  5. The gold-silver lodes occurring in young eruptive rock.
  6. The copper lodes accompanying basic and intermediate eruptive rock.

This classification it is seen only applies to those deposits which are in close relation to an eruptive rock.

The latest systems originate with Beck, 1900 and 1903, and with Bergeat, 1904–1906. These are based more or less upon that of Stelzner. Beck differentiates :

I. Magmatic segregations :
  (*a*) Native metal.
  (*b*) Oxide ores.
  (*c*) Sulphide or arsenide ores.
II. Ores as sedimentary rocks :
  (*a*) Sedimentary deposits of iron ore.
  (*b*) Sedimentary deposits of manganese ore.
III. Epigenetic deposits :
  (*a*) Lodes.
  (*b*) Others.
IV. Secondary deposits :
  (*a*) Older detrital deposits.
  (*b*) Younger detrital deposits.

This grouping, in so far as the magmatic segregations are concerned, agrees entirely with that of Vogt. The subdivisions of the sedimentary deposits are incomplete as they only provide for iron and manganese ores. The group of epigenetic deposits, in that it must include the metasomatic occurrences, the contact-deposits, and a great portion of the ore-beds, is disproportionately large. It is also hardly the best arrangement to place the impregnated deposits under epigenetic deposits, far from the sedimentary deposits with which their geological position is so similar. Again the group of secondary deposits includes only those formed mechanically.

Bergeat gives the following classification which is practically identical with that of Stelzner :

I. Protogene deposits :
  1. Eruptive deposits.
  2. Stratified deposits.
  3. Lodes.
  4. Chamber-deposits.
  5. Metasomatic deposits.
II. Deuterogene deposits :
  6. Metathetic or eluvial gravels.
  7. Alluvial gravels.

From this review it is seen how difficult it is to propound a classification which shall give due consideration at one and the same time to all the characteristic properties of ore-deposits. These characteristics as will be gathered from the chapter dealing with genesis are primarily due to chemical processes ; the more or less finely distributed metal content within the rocks of the crust is brought into molten, aqueous, or gaseous solution, to be later deposited by concentration processes more or less complex. To these chemical impulses many physical factors such as those

expressing themselves in the formation of fractures, add their momentum. The resultant processes of concentration run their course differently as the chemical nature of the particular metal varies, while geological position, form, content, mineral-intergrowth, and association, being dependent upon these processes, vary with them.

Von Groddeck by proposing certain deposits as types, as for instance the siderite, clay-ironstone, Mansfeld, and Schemnitz types, etc., made in effect an important endeavour to obtain a classification into natural genetic groups, an endeavour which in this work will be again taken up though with this difference, that in the place of numerous related types the different groups will appear. In each of these groups those deposits are included which have the same characteristic properties, such properties, established by a comparison of a number of closely-related occurrences, being used as the criteria of genesis. This is the principle of the ' comparative science of ore-deposits.' As the material contained in ore-deposits is a function of genesis, this classification coincides in many cases with that of the metals, and the tin lodes, the gold lodes, etc., still remain as groups.

The complete division into groups upon the above principle eucounters considerable difficulty in that so many deposits, scientifically speaking, have not been sufficiently investigated. This again is an admission that the properties common to the members of the different groups are yet uncertain, and that in isolated cases deposits of questionable genesis may be placed where afterwards it may be proved they do not belong, such as well might happen, for instance, with the fahlbands. As with every natural scientific classification so also with this, no sharp boundary exists between the different groups, and pronounced differences only occur between the types. From these, gradations proceed on either side. The magmatic titaniferous-iron ores, the magmatic nickel-pyrrhotite deposits, the contact-deposits, the tin lodes, the young gold-silver lodes, and the young quick-silver lodes are all in their typical occurrence sharply separated one from the other. Yet there are districts where titaniferous-iron ore occurs with deposits of nickel-pyrrhotite, and contact-deposits with those of tin. In these cases no such sharp separation exists. The gradations from one occurrence to the other do not however render the division into groups untenable, but on the contrary they often furnish further material for the proper understanding of the nature of these groups, and therewith of the genesis of their occurrence.

In a natural classification the groups genetically closely-related must follow close together and this has been kept in view in the following classification. Beginning with the magmatic segregations which represent the deposits nearest to their original source, the sequence of main groups is as follows :

1. Magmatic segregations.
2. Contact-deposits.
3. Fissure cavity-fillings, irregular cavity-fillings, and metasomatic deposits.
4. Ore-beds, sediments more particularly.

Magmatic segregations separated directly from the magma have only since the late 'nineties been more closely investigated in relation to their nature. The contact-deposits formed by endomorphic or exomorphic contact-metamorphism are morphologically and mineralogically fairly sharply-defined, more particularly by their occurrence within the contact-zone, but also by their structure and the presence of characteristic minerals. Separation of these deposits from magmatic segregations is therefore in most cases easy and it is not often that such different views are held as was the case with the deposits of iron ore in the Urals. These two groups, according to the nature of the ore occurring, are further divided into oxide and sulphide ores, etc. The differentiation and separation of the contact-deposits from fissure- and irregular cavity-fillings is however less certain, seeing that fissure-fillings may be formed as one result of contact-metamorphism, the occurrence at Kupferberg in Silesia being a case in point. The different lodes of this group of cavity-fillings are so arranged that those in closest connection with eruptive rocks, namely the pneumatolytically formed tin- and apatite lodes, are given first, then the quicksilver lodes, the young gold-silver lodes, the old gold lodes, and the silver-lead occurrences, all of which may be regarded as in greater part formed by the thermal after-effects of eruptive phenomena ; and finally those deposits, such as the garnierite veins, which have been formed by secondary processes. A classification of the lodes according to the rock in which they are found is not possible of achievement, although the tin lodes occur exclusively in granite or in the allied dykes and sheets. The majority of the lodes occurring in undoubtedly close connection with eruptive rocks are moreover not observed to be associated with any one particular rock but rather with an eruptive epoch. The young gold-silver lodes for instance are found as much in connection with rhyolite as with dacite, andesite, etc.

The separation of the metasomatic deposits from the fissure- and irregular cavity-fillings, as was previously the custom, in view of the close relation between the two classes of deposits, can now no longer be maintained. Although with complete alteration the metasomatic deposits in relation to form and content occasionally show great similarity to typical ore-beds, it is nevertheless natural when discussing the different groups of lodes to discuss at the same time the metasomatic deposits which so often accompany them.

The number of the occurrences to be counted as ore-beds is not yet settled. Properly speaking only those deposits should be so reckoned which are actually sediments, that is younger than their foot-wall and older than their hanging-wall. In many cases however where deposits occur interbedded it is not yet possible to decide whether they were originally so deposited or whether the ore has not been introduced subsequently. A case in point is that of the Witwatersrand conglomerates.

The pyrite deposits also present great difficulty. While formerly these wherever they occurred were all classed together, investigation during the last few years has shown that such simplicity does not exist,[1] but that such deposits may be of very different genesis. That for instance at Meggen represents most probably a sedimentary occurrence, while the neighbouring occurrence at Schwelm is doubtless of metasomatic origin. Those of Norway again, according to Vogt, are undoubtedly to be regarded as magmatic segregations.

Under ore-beds therefore a number of deposits of sedimentary formation are in the first instance discussed, and then some bed-like or apparently bed-like deposits the genesis of which is doubtful.

On the above lines the following complete classification is founded:

I. Magmatic segregations:
  (*a*) Oxide ores:
    1. Chromite group.
    2. Titaniferous-iron group.
    3. Iron and apatite-iron group.
  (*b*) Sulphide ores:
    1. Nickel-pyrrhotite group.
    2. Intrusive pyrite group.
  (*c*) Native metals:
    1. Nickel-iron group.
    2. Platinum group.

II. Contact-deposits:
  (*a*) Oxide ores:
    Iron group.
  (*b*) Sulphide ores:
    Lead-zinc and copper group.

III. Cavity-fillings, and metasomatic deposits:
  1. Tin lodes.
  2. Apatite lodes.
  3. Quicksilver lodes.
  4. Young gold-silver lodes.

[1] Krusch, *Untersuchung und Bewertung der Erzlagerstätten*, p. 301.

5. Old gold lodes.
6. Lead-silver-zinc lodes.
7. Metasomatic lead-silver-zinc deposits.
8. Antimony lodes.
9. Iron lodes.
10. Metasomatic iron deposits.
11. Manganese lodes.
12. Metasomatic manganese deposits.
13. Copper lodes.
14. Metasomatic copper deposits.
15. Pyrite lodes.
16. Metasomatic pyrite deposits.
17. Native-copper deposits.
18. Nickel-cobalt-arsenic veins.
19. Nickel-silicate veins.

IV. Ore-beds :

(*a*) Iron-ore group :

1. Lake- and bog-iron deposits.
2. Oolitic deposits.
3. Carbonaceous and clay ironstone.
4. Chamosite and thuringite.
5. Magnetite, specularite, and hæmatite.
6. Nodular iron deposits.

(*b*) Manganese deposits.
(*c*) Copper-shale group.
(*d*) Fahlband group.
(*e*) Pyrite deposits.
(*f*) Witwatersrand ore-beds.
(*g*) Sulphide lead-zinc deposits.
(*h*) Antimony deposits.
(*i*) Tin gravels and gravels of the noble metals.

MAGMATIC SEGREGATIONS

LITERATURE

J. H. L. Vogt. 'Bildung von Erzlagerstätten durch Differentiationsprozesse in basischen Eruptivmagmata,' Zeit. f. prakt. Geol., 1893.

Comprehensive geological and petrographical investigation prosecuted during the last decades has shown that the eruptive rocks of varying aggregation embraced within a so-called 'Petrographical Province,' in relation to their chemical composition, have certain characteristic properties in common. Between the rocks of extreme composition there is usually an almost unbroken series the members of which are to be regarded as chemical gradations. The different rocks of such a province may consequently be said to exhibit a blood-relationship or consanguinity.

This phenomenon may only be explained in that the differently aggregated rocks found existing in an eruptive field are to be referred back to a single stock magma, which by magmatic differentiation became separated into fractional magmas, in that some of its components suffered transference or migration.

W. C. Brögger in a number of works between the years 1886 and 1898 called attention to the fact that in magmatic differentiation those components are found segregated which during cooling first become crystallized, and that accordingly there exists a parallelism between the sequence of crystallization and that of differentiation, and again between this latter and the sequence in volcanic eruption. J. H. L. Vogt in a recent work[1] explains how that magmatic differentiation follows the same physico-chemical laws as those which hold good for crystallization, that is the passage from the liquid to the solid state. Those minerals which would crystallize first proceed in the anchi-monomineral direction whereby the remaining magma in its chemical relations approaches the condition of an eutecticum, and anchi-eutectic magmas result. With most eruptive rocks crystal-

[1] '*Anchi-monomineralische und anchi-eutektische Eruptivgesteine*,' *Ges. d. Wiss.*, Christiania, 1908.

lization first begins with what may be called the ore-minerals, such as magnetite or titaniferous magnetite, specularite, ilmenite, zircon, apatite, pyrite, and occasionally also spinel, etc. At a somewhat later stage of consolidation the ferro-magnesium silicates such as mica, the hornblende and pyroxene minerals, and olivine, crystallize. It is in agreement with this sequence that, apart from some exceptions, just these components are subject to migration in magmatic differentiation.

The processes which in time past led to the formation of the basic segregations found in many plutonic rocks, the basic borders of many dykes, and the melanokratic diaschist dykes of many eruptive areas, are known generally. All these products of magmatic differentiation are characterized by an increase in iron minerals, chiefly titaniferous iron, in ferro-magnesium silicates, and generally in the anorthite components of the felspars. As will be more closely discussed when describing the occurrences of titaniferous-iron ore, in many cases this enrichment of heavy minerals has proceeded so far that such segregations consist exclusively or preponderatingly of one ore-mineral. Accordingly, from a genetic point of view, whenever such enrichment is pronounced, the particular aggregates are to be regarded as anchi-monomineral or perhaps even as pure monomineral eruptive rocks. Sometimes, as illustrated in Fig. 2, the segregation took place *in situ*; in most cases however it was only after becoming enriched that the magma was forced up, forming then differentiated lodes or streaks in the eruptive, or exceptionally in the country-rock. Such lodes or streaks are illustrated in Figs. 1, 13, 15, 16, 141, and 170.

In addition to these magmatic segregations, the pneumatolytic and the contact-metamorphic deposits must also be considered, both in genesis and in space, as occurring in close relation to eruptive magmas. There is this difference however, that while the magmatic segregations result from a single process, that of magmatic differentiation, in the case of the other, deposits the metal after such differentiation was taken up in aqueous or gaseous solution and deposited later by other processes. It is natural therefore that in the majority of cases the magmatic deposits are quite distinct from the related pneumatolytic and contact-metamorphic deposits. Occasionally gradations such as would result when the process of differentiation was accompanied by pneumatolytic phenomena, occur.

Magmatic segregations according to their content are divided into oxide, sulphide, and metal deposits. This classification, originally proposed in 1893 by Vogt, has been adopted in the new text-books by Beck and Stelzner-Bergeat, and in a large number of other works which have appeared subsequent to its proposal by Vogt. It differs from the mineralogical

sequence which usually places the metals first, then the sulphides, and finally the oxides, because in the study of ore-deposits the oxide and sulphide magmatic segregations are incomparably more important than those containing metals, which in general are only interesting mineralogically and which in relation to their genesis are not entirely beyond question. The description of the oxides before the sulphides is justified because among the former some of the largest ore-deposits of the world are found, such for instance as that of Kiirunavaara.

A. OXIDE SEGREGATIONS

1. Chromite Deposits in Peridotite and Serpentine

LITERATURE

J. H. L. Vogt. Zeit. f. prakt. Geol., 1894, pp. 384-393. Report of the sixth international Geological Congress, Zürich, 1894, pp. 382-392.

All the chromite deposits yet known occur in peridotite or in the serpentine arising from the decomposition of that rock, though the discovery of new deposits in pyroxenite or olivine-pyroxenite, so closely allied to peridotite, may be regarded as not impossible. In most cases the country-rock of such deposits appears completely serpentinized though in a few cases, such as at Hestmandö in northern Norway, at Mount Dun in New Zealand, and at Kraubat in Steiermark, the rock is either not altered at all or altered but very little. Including the varieties dunite consisting almost entirely of olivine; saxonite or harzburgite consisting of olivine and enstatite; wehrlite consisting of olivine and diallage, and often also hornblende; and lherzolite consisting of olivine, enstatite or bronzite, and diallage, peridotite is characterized by a never absent original content of chromium sesqui-oxide, Cr_2O_3, ranging generally from 0·2–0·5 per cent but reaching exceptionally to 1·0 per cent.[1] In these rocks the chromium is found chiefly as chrome-spinel or picotite $(Mg,Fe)(Al,Cr,Fe,)_2O_4$, or as chromite $(Fe,Mg)\ (Cr,Al,Fe)_2O_4$, but also to smaller extent in chrome-diopside, bronzite, mica, and chrome-garnet, etc. In dunite, saxonite, etc., which in general contain but traces of titanic acid, iron and titaniferous iron, otherwise so widely distributed in eruptive rocks, are almost entirely wanting. From this the general statement may be made that the titaniferous iron in gabbro is replaced in peridotite by chromite and picotite, the crystallization of which took place in early stages of the rock's consolidation.

The deposit of chromite which has been most scientifically investigated

[1] See p. 153; also *Zeit. f. prakt. Geol.*, 1898, p. 231.

is that mentioned above as occurring on the island of Hestmandö off the northern coast of Norway. This was examined by Vogt. Within an area about 70 km. long and 40 km. wide situated inside the Polar Circle there occur at least one hundred laccoliths of peridotite generally of the varieties dunite and saxonite. Of these the largest has a superficies of about 0·6 sq. km. while most of the others reach only 0·01–0·05 sq. km. Almost all contain deposits of chromite, these occurring far more often in the central portions of the eruptive mass than around the periphery. These deposits consist partly of clean ore and partly of chromite more or less mixed with olivine and enstatite. Such mixtures, containing at the lowest 3–10 per cent of Cr_2O_3 and at the highest 60–80 per cent, constitute chrome-peridotite, or chrome-dunite, chrome-saxonite, as the case may be, and illustrate

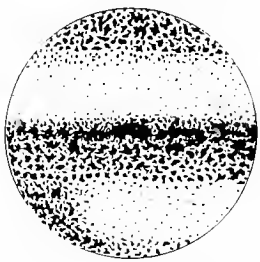

FIG. 167. — Chromite-saxonite, the chromite content varying between 3 and 70 per cent. The banded appearance is that of fluid structure. Illustration from Hestmandö; two-thirds natural size. Vogt, *Zeit. f. prakt. Geol.*, 1894.

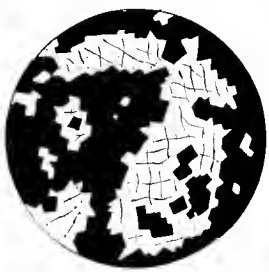

FIG. 168.—Chromite-dunite, consisting of chromite and olivine. Ramberget near Hest mandö; magnified 40 times. Vogt, *Zeit. f. prakt. Geol.*, 1894, p. 391.

the petrographical transition from ordinary rock to the more or less clean ore-deposit. Fig. 168 represents a thin section of chrome-dunite showing chromite as idiomorphic dark crystals embedded in olivine quite undecomposed. As illustrated in Figs. 13, 141, 169, and 170, the occurrences are found sometimes as streaks and sometimes as irregular veins or bunches. Fig. 13 shows a lode-like series of such bunches of clean chromite (black) with others rich in enstatite (hatched), in normal saxonite (dotted). This short description of the deposits at Hestmandö may be taken as typical for the occurrence of chromite deposits in general.

Numerous investigators, as von Groddeck,[1] A. Helland,[2] A. Cossa and A. Arzruni,[3] and L. de Launay,[4] advocated the view that the chromite deposits were formed at the decomposition of chromium-bearing peridotite to serpentine, but as these deposits have also been found within

[1] *Lehrbuch*, 1879.
[2] *Ges. d. Wiss.*, Christiania, 1873.
[3] *Zeit. f. Krist. u. Min.*, 1883.
[4] *Formation des gîtes métallifères*, 1893.

undecomposed peridotite, it is evident that this view cannot be correct. As Vogt pointed out as far back as 1894 these deposits are rather the products of magmatic separation, and the chromite in peridotite plays the same part as the titaniferous iron in gabbro. The chromite deposits in peridotite show accordingly the same geological, petrographical, and morphological characteristics as those of titaniferous iron in gabbro, and the general genetic statements afterwards enumerated in connection with the titaniferous-iron deposits hold good also for the occurrence of chromite. In addition to this well-defined analogy, the gradations from ordinary peridotite through chrome-peridotite to clean ore are further evidence of the mag-

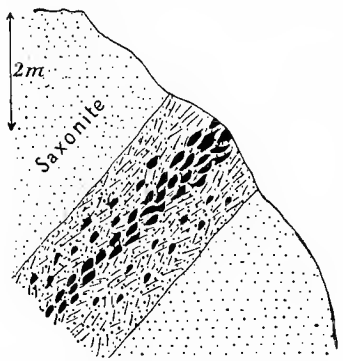

FIG. 169. — Differentiated lode of chromite-saxonite, consisting of chromite, olivine, and enstatite, in normal saxonite. Varnäs near Hestmandö. Vogt, *Zeit. f. prakt. Geol.*, 1894, p. 390.

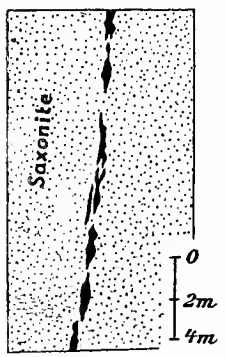

FIG. 170. — Differentiated lode of chromite-dunite in saxonite; length of lode, 40–50 m.; width, 0·1–0·8 m. Varnäs near Hestmandö. Vogt. Fig. 141 reproduces a portion of this lode on a larger scale.

matic origin of these deposits. Finally the order of crystallization, chromite first and olivine afterwards, plainly indicates that the chromite crystallized from a magma. The view first put forward by Vogt that chromite deposits are due to magmatic differentiation has been endorsed by all later investigators who have carried out independent work upon this subject, and in this connection the researches of J. H. Pratt [1] and of Fr. Ryba [2] are especially important.

In the formation of peridotite and the segregation of chromite two different stages in differentiation must be recognized. In the first place the peridotite magma was formed from the stock-magma which may have had the composition of an olivine-gabbro, etc., and then from

[1] 'The Occurrence, Origin, and Chemical Composition of Chromite,' *Trans. Amer. Inst. Min. Eng.*, February 1899; and *Amer. Jour. of Sc.* Vol. VI., 1898, and Vol. VII., 1899.

[2] 'Beitrag zur Genesis der Chromeisenerzlagerstätte bei Kraubat in Obersteiermark,' *Zeit. f. prakt. Geol.*, 1900.

within the peridotite magma the chromite segregations arose by separate differentiation. The two stages, distinct but following one another, are illustrated in the diagram Fig. 171, which is taken from Vogt's work *Über anchi-monomineralische und anchi-eutektische Eruptivgesteine.*

With the Norwegian chromite deposits, both with those to the north and those in the district of Röros-Dovre, there exists a certain relation between the size of the mass of peridotite, or serpentine as the case might

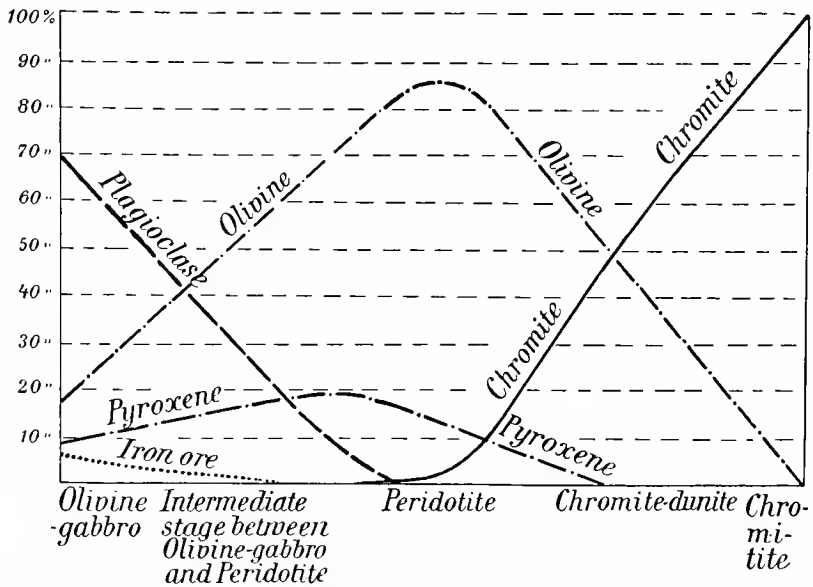

FIG. 171.—Differentiation diagram. To the left the composition of a stock magma; in the middle that of peridotite; and to the right that of the segregated chromite.

be, and that of the chromite deposit found occurring within it. It may indeed be said that small eruptive masses carry only small deposits while the larger deposits are only found in masses of considerable size, probably because the amount of Cr_2O_3 in a small peridotite magma would not be sufficient to form larger deposits. It must be remarked however that it is far from being the case that all peridotite occurrences contain deposits of chromite; indeed several extensive complexes of peridotite and serpentine have proved themselves to be free from such deposits. The phenomena of differentiation have consequently not been operative in all peridotites alike.

The most important Norwegian chromite deposits lie at Feragen in the neighbourhood of Röros in a serpentine mass, which has an area

of about 15 square kilometres. The principal mine, Rödtjern by name, works a streak-like lode of serpentinized chrome-peridotite containing bunches of pure chromite which break cleanly away from the serpentine country-rock. Similarly to the case illustrated in Fig. 170, this occurrence is not one of concentration *in situ* but one of a lode-like injection or intrusion of material previously segregated by differentiation in depth. Other occurrences somewhat smaller lie in the neighbouring serpentine mass of Rödhammeren which has an area of about 5-6 square kilometres. These two fields together since 1830 have yielded about 20,000 tons of chromite.

In serpentine, the alteration-product of peridotite, chromite is accompanied by those minerals which characterize this alteration, namely in the first place by serpentine with antigorite and serpentine-asbestos, then

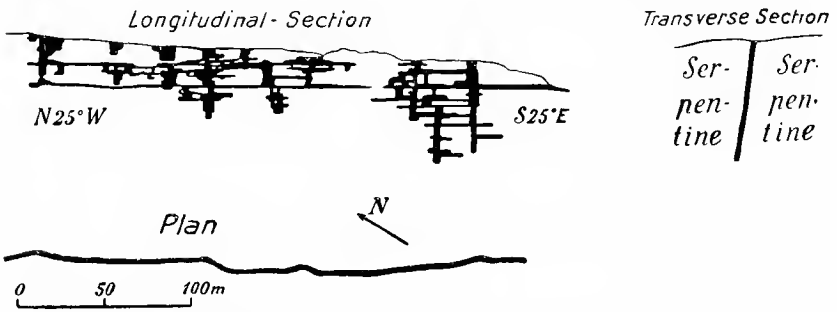

FIG. 172.—Longitudinal section, transverse section, and plan of the Rödtjern mine; from the mine plans of the Röros Mining Company.

often by magnesite, dolomite, talc, chlorite, asbestos, and brucite; and finally more seldom by chrome-mica, chrome-garnet, and chrome-ochre. From the small nickel content of the original peridotite, zaratite, a basic hydrous nickel-carbonate is occasionally formed as a coating upon crevices within the chromite. In a manner analogous to the separation of iron to form magnetite during the serpentinization of olivine rich in iron, so also during the alteration of chrome-diopside and of other chrome-silicates may chromite be formed as a secondary deposit in the crevices and cracks of the remaining minerals.[1] This separation has however so far as is known never led to a concentration of chromite sufficiently large to form of itself a useful deposit.

The most important chromite occurrences at present are in Asia Minor, especially at Makri near the south-west coast of Anatolia, practically opposite the island of Rhodes; and at Daghardy south and south-west of Olymp;[2] in Greece, at Burdaly in Thessaly, and upon the island of

[1] B. Baumgärtel, *Tscher. Min. Petrogr. Mitt.* XXIII., 1904
[2] K. E. Weiss, *Zeit. f. prakt. Geol.*, 1901, p. 249.

Skyros; in New Caledonia, in the Tiebaghi hills and on Mount Dere; and in Canada. In addition, a large number of occurrences which have occasionally been worked on a small scale are known in the United States; in places in Australia and New Zealand; in the East Indies; in the Caucasus; in European Turkey; in Servia, Bosnia, Herzgovina; at Orsova in the Banat; at Kraubat in Steiermark; in the Bukowina; and in Norway, etc. The occurrences near Ekaterinburg and Nischne Tagilsk in the Urals, formerly so often mentioned, have for many years no longer been of any importance. Their fame arose from the circumstance that at the birth of the chrome colour industry, the chromium ore was first obtained from the Urals. To-day Russia no longer exports but actually imports this ore. Germany too is poor in chromium, the occurrences at Silberberg, Grochau, and Frankenstein in Silesia, being small. The best ore comes at present from Asia Minor, in greater part from Daghardy, Kemikli, and Makri. On account of the irregularity of the deposits at these places, the geological occurrence of which is identical to that of those found in Norway, it is only very seldom possible to conduct mining systematically, and in consequence the miner usually lives from hand to mouth. The search for ore, the winning of the irregularly distributed bodies, and their further preparation for the market, are consequently generally left to tributers or peasants from whom the ore is purchased. The mineral-merchant confines himself therefore to making contracts for delivery, in the fulfilment of which he must see that the cleanness of the ore satisfies the requirements of the market.

The yearly consumption of chromite in 1890 was about 20,000 metric tons, most of which came from Asia Minor. Since then it has risen to 80,000 tons. It is used particularly in the production of chrome-steel, chrome colours, and other preparations, and also for firebricks, etc. The mineral chromite, in which part of the Cr_2O_3 is generally replaced by Al_2O_3 or Fe_2O_3 and some of the FeO by MgO, usually contains 52–58 per cent of Cr_2O_3; 5–15 per cent of Al_2O_3; 5–10 per cent of MgO; and 25–40 per cent of iron oxides. The ore marketed, in consequence of contamination by magnesium silicates, does not usually contain more than 50–52 per cent of Cr_2O_3. The price fetched by 50 per cent ore in European ports has latterly been about 70 shillings per ton.

Segregations of Corundum in Peridotite.

The deposits of corundum in North Carolina investigated by J. H. Pratt [1] constitute another case of magmatic segregations in peridotite. In these occurrences the corundum is accompanied by spinel, enstatite, etc.

[1] *Amer. Jour. of Sc.* Vol. VI., 1898; and Vol. VIII., 1899.

In contrast however to the deposits of chromite and titaniferous iron these deposits of corundum occur around the periphery of the eruptive masses and generally, like the nickel-pyrrhotite deposits to be described later, immediately at the margin.

2. The Titaniferous Magnetite and Ilmenite occurrences in Gabbro, Labradorite, Augite-Syenite, Nepheline-Syenite, etc.

LITERATURE

J. H. L. Vogt. 'Bildung von Erzlagerstätten durch Differentiation,' Zeit. f. prakt. Geol., 1893, 1894; 'Weitere Untersuchungen über die Ausscheidungen von Titaneisenerzen in basischen Eruptivgesteinen,' ibid., 1900–1901.—J. F. Kemp. 'A Brief Review of the Titaniferous Magnetites,' School of Mines Quarterly, New York, 1899. In these works a review of the various occurrences and of the articles concerning them is given. The occurrences in Norway, for instance, are described by Th. Kjerulf, T. Dahll, H. Reusch, J. H. L. Vogt, C. Fr. Kolderup; in Sweden by A. Sjögren, A. E. Törnebohm, W. Petersson, Hj. Sjögren, A. G. Högbom, and others; in Finland by H. Blankett; in Canada by H. S. Hunt, B. J. Harrington, E. J. Chapman, R. W. Ells, A. J. Rossi, F. D. Adams, F. J. Pope; in the United States by J. F. Kemp, M. E. Wadsworth, M. B. Yung, S. F. Emmons, G. H. Williams, N. H. and H. V. Winchell, J. H. Pratt, and others; in Brazil by Orville A. Derby, and E. Hussak. Among later articles are: C. H. Warren. 'The Petrography and Mineralogy of Iron Mine Hill, Cumberland,' Amer. Jour. Sc. Vol. XXV., 1908.—J. H. L. Vogt. 'Über die korundführenden Rödsand-Titaneisenerzlagerstätten in Norwegen,' Zeit. f. prakt. Geol., 1910; 'Über das Spinell. Magnetit-Eutektikum (mit besonderer Besprechung der Titanomagnetit-Spinellite)' in Ges. der Wiss., Christiania, 1910. The following exposition is more particularly based upon the works of Vogt.

In certain basic and intermediate eruptive rocks having a silica content up to about 58 per cent, particularly in gabbro, olivine-gabbro, olivine-hyperite, norite, olivine-norite, and in labradorite or anorthosite, but more seldom in augite-syenite and nepheline-syenite, numerous occurrences of titaniferous magnetite and of ilmenite are found scattered over the globe, all of which are connected by intermediate stages with the particular eruptive rock in which they occur. If those occurrences in which the ore content is still relatively low be taken to represent the first stages of concentration it is then the titaniferous iron and the ferro-magnesium silicates, particularly olivine, hypersthene, augite and at times hornblende also, which have become concentrated. Such ores or rocks which are comparable to other basic segregations, are termed titanomagnetite-gabbro or -norite, or ilmenite-gabbro or -norite if some plagioclase be still present.

With further concentration this plagioclase gradually but completely disappears and ores or rocks arise which consist only of ore-minerals and ferro-magnesium silicates, and which are then termed titanomagnetite-olivinite-hypersthenite-pyroxenite, or ilmenite-olivinite-hypersthenite-pyroxenite, etc. With still further concentration the ferro-magnesium silicates give place more and more to the titaniferous iron till finally almost clean titaniferous-magnetite or ilmenite remains. This frequently

carries some spinel of the variety titanomagnetite-spinelite, or exceptionally by enrichment in alumina or aluminium silicate titanomagnetite-corundite arises, and this also often contains spinel.

In some cases such segregations are named after the locality in which they occur, as for instance jacupirangite after Jacupirango in Brazil, though it is preferable to use a nomenclature which will at once suggest something of the composition of the rock concerned. In the table on the next page the compositions of several parent eruptive rocks are given together with others of segregations found occurring within them.

That the deposits here being discussed actually arise by magmatic differentiation follows in the first place from their regular connection with certain eruptive rocks and then also from the regular steps by which the passage from ore to rock may be traced. In addition, the evidences of pneumatolytic action are completely wanting. Their formation rests accordingly upon a purely magmatic differentiation unaccompanied by independent pneumatolytic processes. This process of differentiation is identical in principle to that which brings about the basic margin of dykes, the basic segregations in the plutonic rocks, and finally in general the formation of melanokratic rocks. There is consequently a chemical analogy between the analyses of titan-basalt and melilith-basalt, Nos. 2 and 3 in the above-mentioned table, and those of many segregations which represent the first stages of concentration, the only difference being that with the segregations differentiation has proceeded much further than it has with the ordinary melanokratic rocks. The course of this magmatic differentiation is explained by the diagrams Figs. 173 and 174 with which also Fig. 171 may be compared.

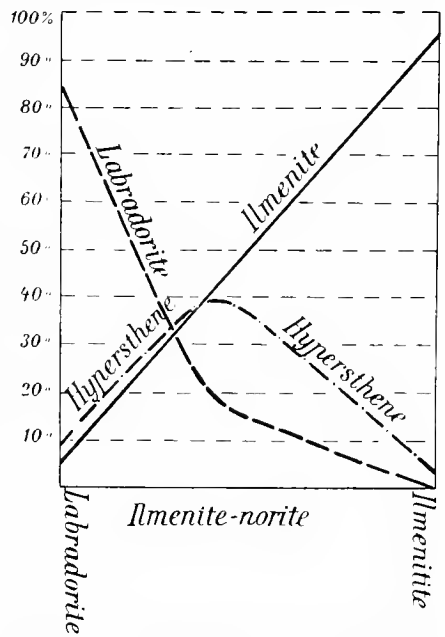

Fig. 173.—Differentiation diagram of the magmatic segregations at Ekersund-Soggendal. Vogt.

The ilmenite of the final product of differentiation, ilmentite, at Ekersund-Soggendal, of which a segregation diagram is given in Fig. 173, contains 3–5 per cent of MgO in the form of a definite combination, $MgTiO_3$.

No.	SiO_2	TiO_2	Cr_2O_3	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	H_2O	Total.
1*a*	52·80	0·50	...	17·80	1·20	4·80	..	4·80	12·90	3·00	0·50	...	...	1·20	99·50
1*b*	40·20	4·70	...	9·50	9·70	12·20	0·40	8·00	13·10	0·80	0·20	...	0·40*	0·50	99·70
1*c*	29·50	9·20	...	3·80	17·80	18·20	0·3.	8·70	10·00	0·20	0·10	...	0·40*	1·00	99·20
2*a*	44·55	4·52	...	12·48	2·81	8·54	...	10·85	7·99	4·04	2·57	0·70	...	0·74	99·64
2*b*	44·83	6·88	...	11·73	1·35	11·79	...	5·50	9·63	3·84	1·10	2·14	...	0·91	99·50
3*a*	38·87	4·79	3·06	11·94	4·02	6·00	...	15·24	10·87	2·59	1·64	...	...	2·82	90·02
3*b*	35·84	8·85	2·84	10·48	7·25	6·62	...	12·95	10·90	5·53	1·51	...	...	1·92	100·77
4*a*	47·88	1·20	...	18·90	1·39	10·45	0·16	7·10	8·36	2·75	0·81	0·20	0·07	0·61	100·02
4*b*	17·90	15·66	0·51	10·23	15·85	27·94	...	6·04	2·86	...	...	0·04	0·14	1·33	99·06
5*a*	44·77	5·26	...	12·46	4·63	12·99	0·17	5·34	10·20	2·47	0·95	0·28	0·26	0·60	100·75
5*b*	11·73	12·31	...	6·46	30·68	27·92	...	3·35	3·95	0·50	0·26	0·82	0·04	0·64	99·18
6*a*	53·50	0·30	...	27·50	2·8		...	1·00	9·50	4·70	0·80	0·005	...	...	100·00
6*b*	31·59	18·49	...	8·54	2·36	24·52	...	10·70	2·25	1·03	0·15	0·02	...	...	99·65
6*c*	5·70	39·20	...	2·89	18·59	30·00	0·60	2·80	...	...	...	...	...	...	99·78
6*d*	0·60	41·75	...	...	22·11	31·01	0·28	3·15	0·55	...	...	0·015	Tr	...	99·95
7	24·74	9·53	...	6·99	24·58	21·86	0·69	9·23	2·88	...	...	0·07	0·01	...	100·61
8	20·85	9·93	...	5·55	45·62		...	16·45	0·73	...	...	...	...	...	99·13
9	21·25	6·30	...	5·55	43·45		0·40	18·30	1·65	...	...	0·13	0·013	2·60	99·66
10	16·17	7·14	...	5·34	35·20	23·22	0·46	7·56	1·84	...	...	0·07	1·02	0·40	98·75
11	10·37	8·17	0·12	5·01	37·35	28·82	0·31	4·23	4·40	0·57	0·12	0·09	0·04	0·47	100·61
12	7·52	10·21	0·11	4·45	46·67	22·10	0·23	3·13	2·17	0·52	0·22	0·07	0·82	0·37	99·28
13	4·08	14·25	0·20	6·40	33·43	34·58	0·45	3·89	0·65	0·29	0·15	0·016	0·044	1·32	99·75
14	2·32	15·41	...	4·06	73·87		...	3·66	0·13	...	...	0·009	1·42	...	100·88
15	1·11	18·82	...	6·18	39·18	30·73	0·46	4·04	...	...	...	0·08	0·02	0·26	100·95
16	7·30	8·30	...	6·93	72.09		...	2·91	1·83	...	...	...	...	...	99·26
17	0·51	2·41	...	39·36	45.86		0·55	7·18	0·47	...	...	0·22	...	1·18	97·74
18	7·75	41·22	...	...	39·00		1·40	7·65	4·14	...	...	0·32	0·013	...	101·51
19	1·91	40·00	...	4·00	20·35	29·57	...	3·17	1·00	...	...	...	...	...	100·00

Remarks upon the Table

No. 1, Banded Tertiary gabbro from the island of Skye. After A. Geikie and J. J. H. Teall; *Quart. Jour.*, 1894. *a*, Gabbro; *b*, dark band; *c*, ultra-basic streak; *, FeS.—No. 2, Titaniferous basalt. After H. S. Washington, 'The Titaniferous Basalts of the Western Mediterranean'; *ibid.* 1907.—No. 3, Melilith-basalt. After U. Grubemann, *Die Basalte des Hegaus*; Diss. Zurich, 1886.—No. 4*a*, Gabbro; No. 5*a*, norite, both from the Adirondacks, New York; Nos. 4*b* and 5*b*, segregations in 4*a* and 5*a* respectively; cited by Kemp.—No. 6*a*, Labradorite; *b*, ilmenite-norite; *c* and *d*, ilmentite from Ekersund-Soggendal, Norway. After Vogt and Kolderup.—Nos. 8, 9, and 10, Titanomagnetite-olivinite from Cumberland Hill in Rhode Island, after Wadsworth; and from Taberg and Inglamåla in Sweden, after Vogt.—Nos. 11 and 12, Segregations in gabbro from Ontario, after Kemp.—Nos. 13, 14, 15, Titanomagnetite-spinelite from Routivare in Sweden, after W. Petersson, *Geol. Fören. Förh.*, 1893; and from Solnör in Norway; cited by Vogt.—No. 16, Corundum-bearing titano-magnetite from Rödsand in Norway; cited by Vogt.—No. 17, Magnetite-corundum-spinel ore in Cortland norite. G. H. Williams, *Amer. Jour. Sc.* XXXIII., 1887; J. H. Pratt, *ibid.* VI., 1898.—Nos. 18 and 19, Ilmenite ores from North Carolina and St. Urbain, Quebec; after Kemp and Adams.

V_2O_3 was determined in 4*b*, 5*b*, 10, 11, 12 to be 0·46, 0·03, 0·33, 0·24, 0·29 per cent respectively; CO_2 in 4*a*, 4*b*, 5*a*, and 5*b* to be 0·12, 0·10, 0·37, 0·32 per cent respectively; Cu in 7 and 9 to be 0·03 and 0·02 per cent respectively; NiO in 4*a*, 11 and 12 to be 0·02, 0·26 and 0·31 per cent respectively; CoO in 11 and 12 to be 0·04 and 0·09 per cent respectively; Nio + CoO in 15 to be 0·07 per cent.

This magnesia content may be explained in that the resultant ilmentite, at the stage of concentration characterized by ilmenite-norite, encountered a magma rich in magnesia.

Fig. 174 illustrates a similar occurrence in the Lofoten Islands, that of segregation within gabbro or anorthite-gabbro. In this case the intermediate stage of titanomagnetite-pyroxenite is rich in Al_2O_3 as well as in MgO, so that the chemical conditions necessary for the formation of spinel are present, conditions which with further differentiation become more pronounced.

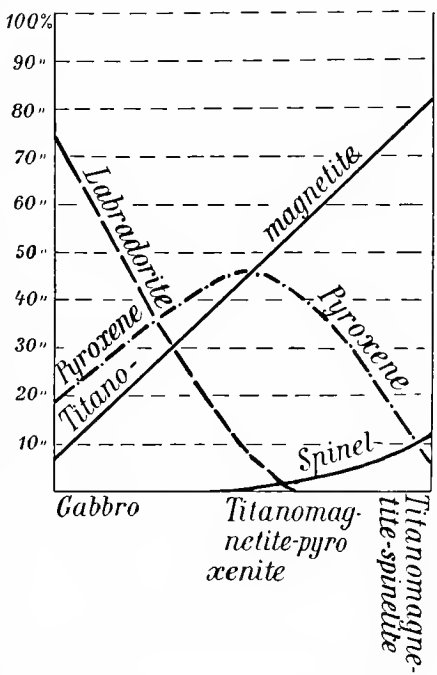

Fig. 174.—Differentiation diagram of the Lofoten ore. Vogt.

The oxide segregations occurring in gabbro, labradorite, augite-syenite or nepheline-syenite, of which about five hundred are at present known, are without exception regularly characterized by containing titanic acid to an extent more or less considerable, a content which rests upon the never-failing presence of this substance in the original magma, though this generally may only have been from 0·3–1 per cent. In one and the same district the amount of titanic acid present, reckoned with reference to the amount of iron, usually varies only within narrow limits. Four analyses of titano-magnetite-spinelite from Solnör in Norway, of which one is given under No. 14, gave amounts of TiO_2 varying between 12 and 15·5 per cent; ten from Routivare in Sweden, one being No. 13, between 11·3 and 14·6; while eighteen analyses of ilmenite from the labradorite of Ekersund and Soggendal contained between 34 and 51·3 per cent of TiO_2, the lower figure being accounted for by some admixture of hypersthene and labradorite. In segregations rich in iron the percentage rarely sinks below 4–5 per cent though strangely enough some magnetite-pyroxenite deposits from Kaljord in Norway, with roughly 50 per cent of iron, do not contain more than one per cent of titanic acid. Those deposits however occur in a monzonite with 58–60 per cent of silica, and not therefore in a gabbro rock in the strict sense of the term.

Titaniferous magnetite or titanomagnetite consists in many cases of a fine or even microscopic mixture of clean magnetite, showing little or no titanium content, with ilmenite. There is evidence of this in the following figures of magnetic concentration taken from the official report of the Norwegian Electro-Metallurgical Commission, 1910.

No.	Composition of the ore treated.		Tons of ore per ton of concentrate produced.	Composition of the magnetically-separated concentrate.	
	Fe.	TiO_2.		Fe.	TiO_2.
	Per cent.	Per cent.		Per cent.	Per cent.
20*a*	35·1	7·2	2·86	69·6	0·4
20*b*	44·7	7·1	2·04	68·5	1·5
21*a*	42·6	8·5	2·00	68·4	1·0
21*b*	49·3	9·0	1·58	68·8	1·2
21*c*	51·2	7·8	1·57	64·6	2·4
22	± 50 0	15·0	2·12	68·6	2·4
23	± 50·0	13·5	1·87	59·1	6·3

No. 20, *a* and *b* are from Heindalen, near Langfjorden, Molde; No. 21, *a*, *b*, and *c*, from the neighbouring district of Rödsand, see No. 16 and Fig. 177; Nos. 22 and 23, titanomagnetite-spinelite from Solnör and Lied, Söndmöre, see No. 14, p. 252.

In these tests the raw ore was reduced to grains with a maximum diameter of 0·1 mm., at which size, in the cases of Nos. 20, 21, and 22, the magnetite and ilmenite were in great part separated from one another, while in 20*a* the separation was almost perfect. With No. 23 on the other hand, seeing that the separation was not so good, the mineral individuals were apparently to some extent smaller than the size to which the ore was crushed. In a work dealing with the microstructure of the Brazilian titaniferous-iron ores [1] E. Hussak shows that small crystals of ilmenite were often aggregated upon the octahedral surfaces of the magnetite, sometimes irregularly and sometimes in arborescent form.

As indicated on p. 252 the segregations of titaniferous iron almost invariably carry a small amount of vanadium in the form of V_2O_3 and occasionally a little Cr_2O_3, NiO, and CoO. The amount of apatite or P_2O_5 is almost always low also, though to this rule there are exceptions; it may indeed sometimes happen that the apatite has become more enriched than the iron. The pyrite content also is fairly low. Carbon, apparently in the form of graphite, has been demonstrated by Hillebrand [2] to be present in some iron deposits.

With the titanomagnetite-spinelite, which occurs fairly often in Norway and Sweden and which generally contains 7–12 per cent of spinel, the spinel as porphyritic crystals was the first to separate, leaving a ground-

[1] *Neues Jahrb. f. Min., Geol., Pal.*, 1904, I.

[2] Kemp, *loc. cit.*

mass which, neglecting the silicate minerals and ilmenite, consisted of an eutectic mixture of magnetite and spinel in the proportion of 97 of magnetite to 3 of spinel.[1]

In the case of some Norwegian occurrences two different segregation sequences are found together namely: first, that of titaniferous-iron ore from gabbro rich in iron through titanomagnetite-diallageite and titanomagnetite-spinelite; and second, that of ferro-magnesium silicates from olivine-gabbro through olivine-gabbro with much olivine though little iron, through an olivine rock carrying only about 20 per cent plagioclase, to peridotite without iron. In such cases two different processes of differentiation must have continued their course concurrently in one and the same magma.[2]

Concerning the occurrence, the arrangement, and the distribution of the segregations of titaniferous-iron ore, these in general are similar to those of the chromite occurrences in peridotite, that is to say they are not peripheral deposits, but occur in the central portions of eruptive masses. In addition, as illustrated in Fig. 2, they pass gradually and on all sides of their central core to normal rock, an occurrence explained only by differentiation *in situ*. Still more often however, as illustrated in Fig. 175, they occur as irregular streaks or even as normal lodes sharply separate from the eruptive rock. In this connection the so-called 'Storgang' at Soggendal, a lode of ilmenite-norite in labradorite, is worthy of special mention. This occurrence which has a length of 2·5–3 km. and a width of 30–60 m. possesses, as illustrated in Fig. 1, the proper tabular form of a dyke. Differentiation in this case must have taken place in depth, after which the resultant ilmenite-norite magma was extruded like any ordinary diaschist rock-magma through the already solidified labradorite. This explanation has already been given for the streaks or lodes of chrome-peridotite or clean chromite in peridotite. The occurrences of titaniferous-iron ore found in the old crystalline schists occasionally give evidence of great deformation under pressure, the pyroxenes being often completely uralitized.

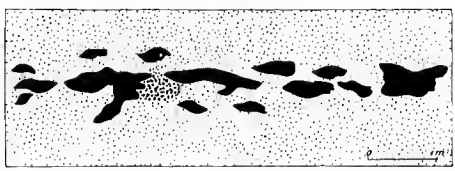

FIG. 175.—Streak of titano-magnetite-spinelite segregations in the labradorite of Andopen in the Lofoten Islands. Vogt, *Zeit. f. prakt. Geol.*, 1900, p. 235.

Titaniferous-iron deposits occasionally reach very considerable dimensions as the following figures show:

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[1] Vogt, *loc. cit.* p. 250.

[2] Vogt, *Zeit. f. prakt. Geol.*, 1900, p. 233; *Anchi-eutektische und anchi-monomineralische Eruptivgesteine*, 1908.

Deposit.	Superficial Extent.	Fe.	TiO_2.
		Per cent.	Per cent.
Routivare in Sweden— Titanomagnetite-spinelite .	300,000 sq. m.	50	±13
Taberg in Sweden— Titanomagnetite-olivinite .	260,000 ,,	31	±6
Storgang in Norway— Ilmenite-norite . . .	125,000 ,,	20	±18

The greater number however are substantially smaller, while some are quite small. In Norway for instance there are a large number of these deposits with areas of 60–5000 sq. m. or even less.

The ores of the above-named deposits were formerly and from time to time smelted in the usual manner in blast furnaces. At the beginning of the nineteenth century for example fifteen small furnaces of this type were fed exclusively with ore from Taberg. To-day however these ores are of little economical importance, partly on account of their comparatively low iron content but also because of the high amount of titanic acid contained which, particularly if some magnesia be present, renders them difficult to fuse. Vogt however is of opinion that the effect of the titanium upon the fuel consumption has been over-estimated; he also points out that from some of the deposits a rich iron concentrate may be obtained by magnetic separation.

Ilmenite ores with 35–40 per cent of TiO_2 and approximately the same amount of iron, are used to a small extent for the production of titanothermit, ferrotitanium, ferrosilicon-titanium, etc.; while by fractional reduction in the electric furnace titanic acid may be obtained. The most important occurrence of such ilmenite ores are found at Ekersund-Soggendal in Norway; in the large labradorite districts of Canada; and in the Adirondacks of the United States.

The Occurrences in Norway

LITERATURE

Vogt. Loc. cit. and Archiv für Mathem. og Naturv. XII., 1887; Geol. Fören. Förh., 1891. See also Vogt's Norges Jernmalmforekomster, Norwegian Geological Department, 1910, No. 51.—C. Fr. Kolderup. Bergens Museums Aarbog V., 1896; and in addition other earlier works.

The best known of these occurrences are the important deposits at Ekersund-Soggendal on the south coast. As indicated in Fig. 143, an eruptive field or petrographical province extends here over about 1450 sq. km. upon land and over an unknown area below the sea. In this a large number of

closely-related eruptive rocks occur, among which labradorite, norite and quartz-norite, monzonite, banatite, adamelite, hypersthene-granite, etc., in addition to many dyke rocks, are worthy of remark. Within the labradorite, differentiated lodes of ilmenite-norite occur, as illustrated in Fig. 1, as also do streak-like segregations of ilmentite, some of which are also found in the norite. Analyses of this labradorite, ilmenite-norite, and ilmentite are given on p. 252 under Nos. 6*a*, 6*b*, 6*c*, and 6*d* respectively.

In Fig. 15 the occurrence of such segregations at Blaafjeld in the neighbourhood of Soggendal is illustrated, while in Fig. 176 the streak-like lode of that occurrence is given later on a larger scale. These deposits are accompanied by dykes of norite-pegmatite and traversed here and there by later basic diaschist dykes from the same eruption. In this district which contains a considerable number of these titaniferous-iron deposits, about 100,000 tons of ore with 36–40 per cent of titanic acid, and from 36–38 per cent of iron have been obtained.

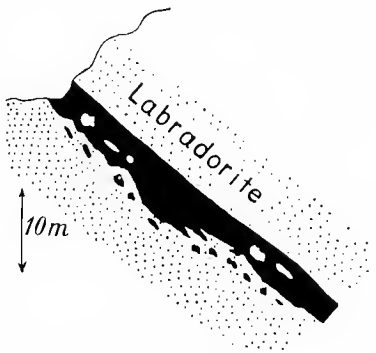

Fig. 176.—Streak-like lode of ilmenite in labradorite. Blaafjeld near Soggendal.

Another field extending from Rödsand to Fanestrand in the neighbourhood of Molde, presents many interesting features. Within an Archæan granite area, 50 km. long and 10 km. wide, a series of small schistose gabbro segregations appear, within at least six of which a number of segregations of titaniferous iron are found, generally with about 50 per cent of iron and 7–9 per cent of titanic acid, and at Rödsand with 1–2 per cent of corundum. This occurrence is illustrated in Fig. 177 and an analysis of a selected sample of the ore is given under No. 16, p. 252. It would appear in this case that out of a granitic stock-magma a gabbro fractional-magma was first separated from which again by further differentiation the ore-deposit arose.

In addition, similar deposits of titaniferous iron are known in at least thirty other areas in Norway.

The Occurrences in Sweden

The mountain of ore at Taberg described as early as 1806 by J. Fr. L. Hausmann[1] and later more particularly by A. Sjögren and A. E. Törnebohm,[2] is well known. In the central portion of a relatively small area of

[1] *Reise durch Skandinavien.*

[2] *Geol. Fören. Förh.*, 1876, 1881, and 1882.

olivine-hyperite—olivine-gabbro with ophitic structure—a ridge about 1 km. long and 400 m. wide rises about 130 m. above its surroundings, this prominence being due to the greater power of resistance which the material of this ridge, consisting chiefly of titano-magnetite-olivinite, was able to present to the destructive effect of the atmospheric agencies. In this occurrence, which is diagrammatically illustrated in Fig. 2, the ore contains only about 31–33 per cent of iron. It was formerly worked in opencut.

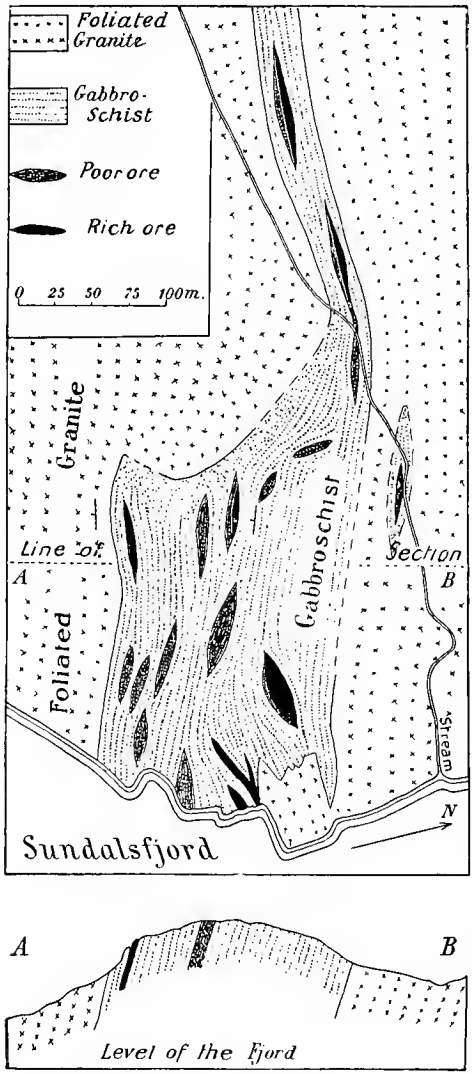

Fig. 177.—Map and section of the Rödsand mining field. Vogt, *Zeit. f. prakt. Geol.*, 1910, p. 65.

At Routivare in northern Sweden another mountain of ore about 1600 m. long and 200–300 m. wide likewise rises 160–180 m. above its surroundings. The country-rock appears to be a foliated and altered labradorite though gabbro also occurs. The ore itself is substantially a titano-magnetite-spinelite composed of magnetite, ilmenite, spinel, olivine, and a pyroxene mineral. An analysis is given under No. 13, p. 252. As seen from Fig. 178 the outline of this deposit is very indented and the occurrence is probably that of a streak on a large scale.[1]

In the small area, presumably of nepheline-syenite, at Alnö several of these deposits occur, some of which are distinguished by containing a considerable amount of apatite, up to 16·47 per cent of P_2O_5.[2]

[1] W. Petersson, Hj. Sjögren, *Geol. Fören. Förh.*, 1893.
[2] A. G. Högbom, *Geol. Fören. Förh.*, 1895.

Occurrences in Brazil.—The nepheline-syenite of Jacupirango and Ipanema in the province of São Paulo also carries deposits of titaniferous iron.[1] In some of these, carrying more CaO, the titanic acid occurs in part as the mineral perovskite, $CaTiO_3$.[1]

Occurrences in Canada.—In the extensive anorthosite areas of Canada many deposits of ilmenite occur with 32 to 50 per cent of titanic acid. One analysis of these is given under No. 19, p. 252. Some, as that at the Saguenay River near Morin, north of Montreal, and that at St. Paul's Bay, 80 km. from Quebec on the St. Lawrence River, reach great dimensions. One on the north bank of the Saguenay River between Chicoutimi and St. John's Lake is 75 m. wide.

Occurrences in the United States.—At Sandford Lake in the Adirondacks, in the state of New York, deposits of titaniferous-iron ore of

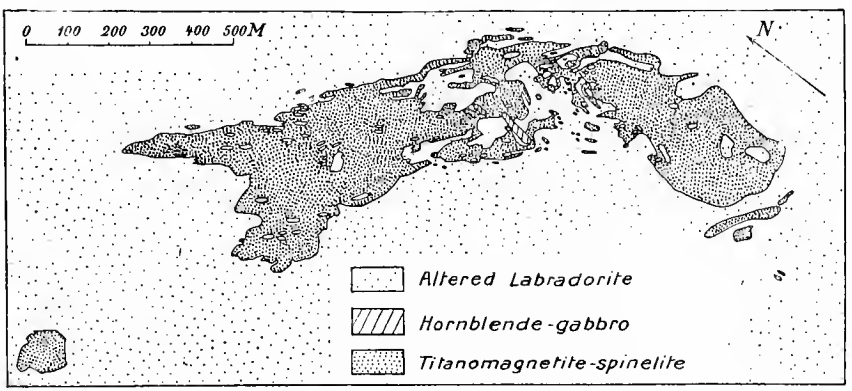

Fig. 178.—Map of Routivare. W. Petersson.

large dimensions and similar to those in Canada occur, in regard to which reference is recommended to the above-quoted work of Kemp, and to other works by that author and by Adams.[2]

3. Deposits of Iron Ore and Apatite-Iron Ore in Acid Rocks

These deposits are free or practically free from titanium and occur in granite or other acid eruptive rock. The Scandinavian Peninsula contains many important deposits, some even gigantic, consisting chiefly of mag-

[1] O. A. Derby, *Amer. Jour. Sc.*, 1891; *Quart. Jour.*, 1891; E. Hussak, *Neues Jahrb. f. Min., Geol. und Pal.*, 1892, II.; *Mineral Mag.* XI., 1895.

[2] Kemp, 'The Titaniferous Iron Ores of the Adirondacks,' *U.S. Geol. Surv. Ann. Rep.*, 1897–1898, III.; *Zeit. f. prakt. Geol.*, 1905, pp. 71–80; and 'The Ore-Deposits of the United States and Canada.' In this latter the Canadian literature of recent years, especially the work of Adams is fully quoted.

netite and subordinately of specularite, which occur in foliated granite, granite-gneiss, or other acid eruptive rock, and which may be regarded as of magmatic origin. To this group belong the economically and scientifically equally important deposits of Kiirunavaara-Luossavaara, Gellivare, etc., in northern Sweden, and the important field of Sydvaranger in Norway, besides many smaller deposits in the Lofoten-Vesteraalen Islands, and those of Lyngrot and Solberg in the neighbourhood of Arendal and Tvedestrand.

The deposits here included vary however not inconsiderably in mineralogical and geological character. They form therefore no such sharply-defined group as the chromite and the titaniferous-iron deposits already described, nor as the nickel-pyrrhotite deposits yet to be described. In addition they in part at least have not been sufficiently investigated, so that different views as to their genesis are at present held. A general review of their common properties is therefore not given but the description is limited to the more important individual occurrences. Those in Norway are described first because genetically they are the more simple.

Norway

LITERATURE

J. H. L. Vogt. Norges Jernmalmforkeomster. Norwegian Geological Department, 1910. No. 51.

The deposits which here receive consideration may, according to Vogt, be divided into the two following subdivisions, though these are connected by intermediate grades.

(*a*) Occurrences with fairly clean iron ore or apatite-iron ore, generally with 55 to 65 per cent of iron, though occasionally with as much as 68 per cent.

(*b*) Occurrences of iron ore banded with quartz, hornblende, epidote, etc., and containing on an average only 35 per cent of iron.

Both classes occur in granite-gneiss fairly rich in orthoclase-microcline and belonging to the fundamental crystalline schists.

Close to the south coast of Norway, at Lyngrot and Solberg, a granite rich in potassium-felspar and containing about 74 per cent of SiO_2, carries a good deal of magnetite in certain zones, forming thereby a rock termed by Kjerulf and Dahll[1] *Eisengranitel.* The clean magnetite, as indicated in Fig. 179, often forms narrow streaks a millimetre, a centimetre, or an inch thick, though in places these become thicker and thicker till finally

[1] Th. Kjerulf und T. Dahll, 'Ueber das Vorkommen der Eisenerze bei Arendal, Näs und Kragerö,' *Neues Jahrb. f. Min., Geol., Pal.*, 1862.

such large masses arise as necessitate separate mines for their exploitation. Work at Lyngrot and Solberg, abandoned between 1850 and 1860, reached a depth of about 150 m. The ore at the latter mine situated quite close to the smelting works at Näs near Tvedestrand, contained on an average

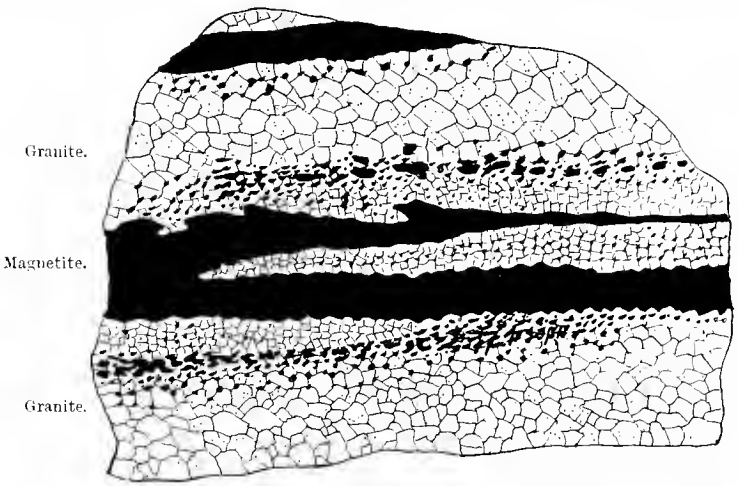

Fig. 179.—Bands of magnetite in granite. Lyngrot. One-half natural size. Vogt.

66–68 per cent of iron, 0·03–0·05 per cent of phosphorus, and a minimal amount of titanic acid. Mineralogically the occurrence is peculiarly interesting in that crystals of zircon up to a centimetre in size were found embedded in the magnetite. At Lyngrot the ore is usually much mixed with apatite, this mineral occurring partly in grains of millet- or pea-size but also in pieces as big as the fist. The occurrence in this respect is such that the ore might often be mistaken for the apatite-iron ore of Gellivare. In addition it carries some hornblende, mica, felspar, quartz, etc. Occasionally also a breccia occurs in which fragments of all the minerals named are found together with pieces of the foliated granite. This breccia, illustrated in Fig. 181, is similar to another occurrence at Norrbotten yet to be described.

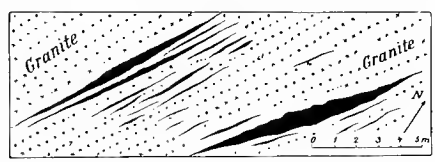

Fig. 180.—Bands of magnetite in foliated granite. Solberg, near Näs.

At Sydvaranger in Finnmarken in northern Norway, at a latitude of 69·6°, near the Russian frontier, there are occurrences of quartz-banded magnetite with about 35 per cent of iron, some of which are extremely important more particularly by reason of their dimensions. These deposits

are found within an area 15 km. long and 2–5 km. wide of red foliated Archæan granite with numerous occurrences of intermediate and basic eruptive rocks, such as quartz-amphibole schists, gabbro, and in places serpentine. The ore is generally an intimate alternation of layers from 1 to 5 mm. thick, these layers consisting respectively of magnetite with

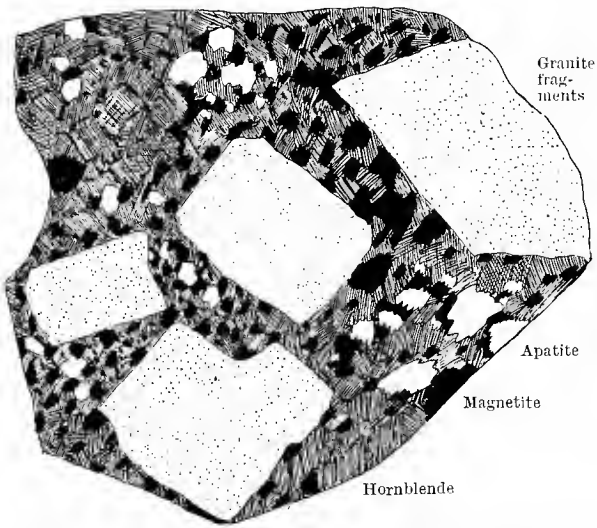

FIG. 181.—Hand specimen from Lyngrot, showing angular fragments of granite (lightly dotted) cemented by magnetite (black), by apatite (white), and by hornblende (hatched). One-half natural size. Vogt.

some quartz and hornblende, and of quartz with some hornblende, magnetite, and occasionally some secondary epidote. This banded ore, illustrated in Figs. 183 and 184, is often folded and crumpled. The composition of the ordinary ore is indicated under No. 1 of the analyses given on page 264, while under No. 2 the result of an especially rich sample is given. The figures under Nos. 3 and 4 belonging to geologically similar ore from Fiskefjorden in the Lofoten Islands are given for comparison.

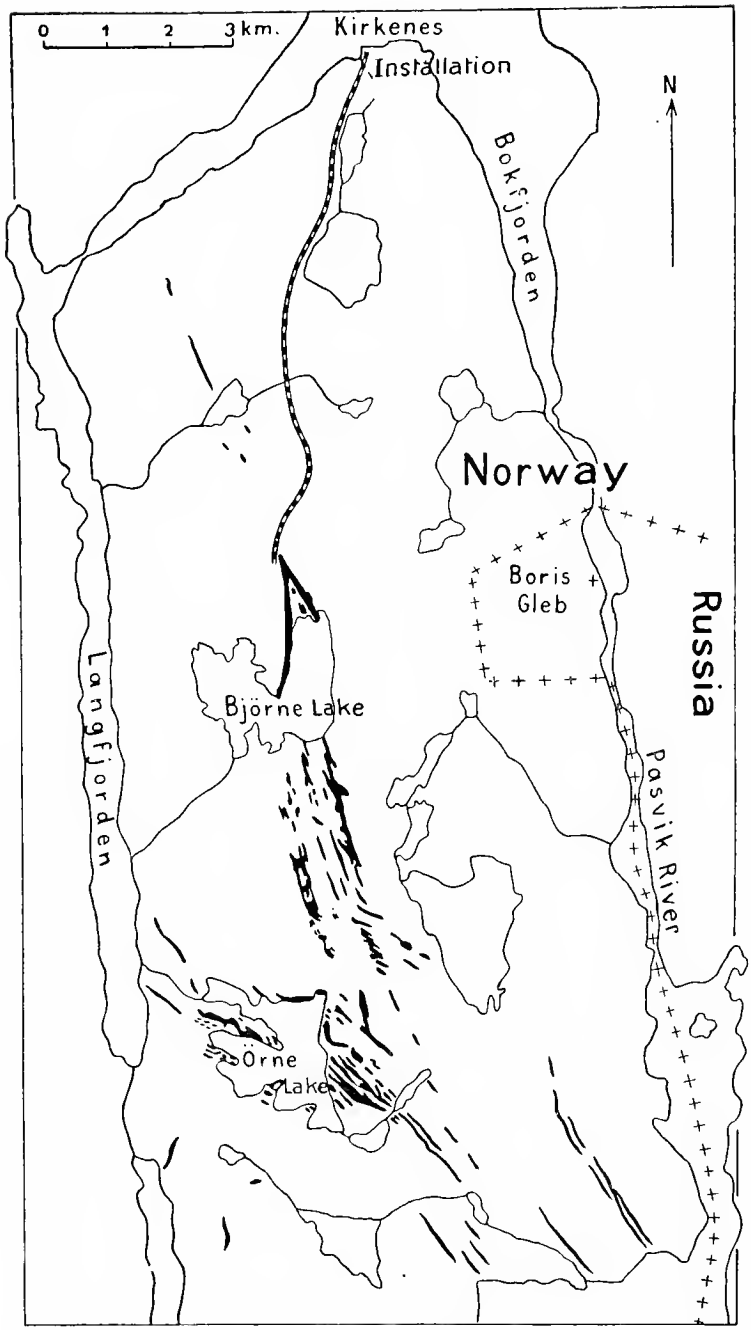

FIG. 182.—Map of the Sydvaranger ironfield showing deposits of iron ore (black).

	Sydvaranger.		Fiskefjorden.	
	No. 1.	No. 2.	No 3.	No. 4.
Fe_2O_3	36·71	40·06	42·63	38·50
FeO	15·40	17·82	20·18	
SiO_2	43·92	35·42	30·05	50·28
Al_2O_3	0·83	1·54	2·41	4·81
MnO	0·58	0·48	0·17	0·22
MgO	1·12	2·60	1·62	3·08
CaO	0·48	2·15	2·13	2·02
P_2O_5	0·07	0·08	0·23	0·55
S	0·04	0·03	0·10	0·36
TiO_2	0·08	0·09	0·33	0·25
Totals	99·23	100·27	99·85	100·08
Iron	37·68	41·94	45·54	27·88

In addition No. 4 also contains 0·01 per cent of copper.

The ore-bodies at Sydvaranger have very variable extension. Some are quite small, 1 m. long by 0·2 m. wide, while others attain very considerable dimensions. Thus the principal occurrence at Björnevand, 8 km. from the port of Kirkenäs, as illustrated in Fig. 185, has an unbroken length of approximately 3 km. with a width from 30 to 150 m.

The composition of the ore is usually fairly uniform and the iron content generally keeps between 30 and 38 per cent. Exceptionally some sections occurring in the deposits at Örnevand and consisting of magnetite, hornblende, and a little epidote, contain from 48 to 56 per cent of iron with an average of 52–53 per cent. The separation of the ore from the granite is always very well defined, sometimes even strikingly so. The ore-bodies are crossed by dykes of granite and of a coarse-grained diabase which is partly fresh and partly very decomposed. Similarly to the occurrences at Taberg, Kiirunavaara-Luossavaara, and Dunderland, here also the larger deposits on account of their greater hardness and resistance stand out as prominences and ridges these naturally being higher the greater the mass of the deposit.

The total extent of these deposits is about 1·25 million square metres. On an average they contain about 35 per cent of iron, 0·04 per cent phosphorus, 0·03 per cent sulphur, and a trace of titanic acid. If only ore-bodies of greater length than 300 m., of width not less than 25 m., and with at least an average of 34 per cent of iron be considered, the extent would be some 750,000 square metres. Richer bodies than these with an average of 52–53 per cent of iron probably occupy only about 6000 square metres.

Approximately 100 million tons of ore with 35 per cent of iron may be worked in opencut, and of this amount about 32 millions at Björnevand

lie above the level of the railway there. Putting all the occurrences together the total amount of ore is estimated at about 2·5 million tons of 35

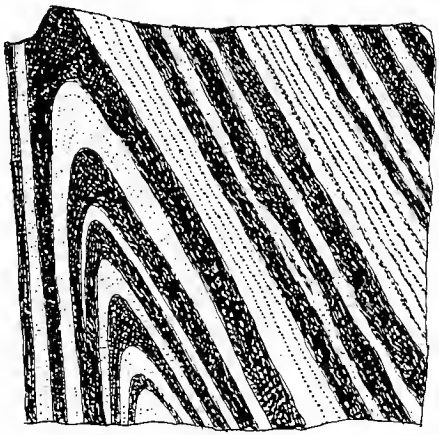

FIG. 183.—Hand specimen of the quartz-banded iron ore from Sydvaranger. Three-quarters natural size. Vogt.

per cent ore per metre of depth, and in addition 20,000 tons of 52–53 per cent. Since the larger bodies extending to 3 km. in length have undoubtedly a considerable extent in depth, the total quantity to a depth of 400–500 m. may be estimated at about one milliard tons with 35 per cent

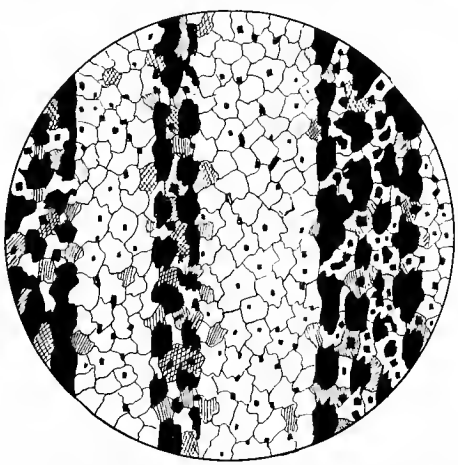

FIG. 184.—Microscopic slide of the Sydvaranger ore, magnified twenty-five times, showing magnetite (black), quartz (white), and hornblende (singly and doubly hatched). Vogt.

of iron. Such an estimate is however for the present only of theoretical interest.

The poor magnetite ore being free from specularite allows itself to be

readily concentrated by wet magnetic processes. To produce one ton of concentrate containing 67 per cent of iron and 0·008 per cent of phosphorus, about 2·3 tons of ore containing 35 per cent of iron are necessary. Important equipments are now in the course of erection from which, beginning with the year 1911, it is expected to produce about 600,000 tons of concentrate and briquettes annually.

Lofoten-Vesteraalen.—In the Archæan granite district of the Lofoten Islands, the position of which is indicated in Fig. 188, a number of ironfields are known, among which some, as for instance those of Fiskefjord, Blokken, Sigerfjord, Öksfjord, Gullesfjord, etc., on the island of Hindö, carry magnetite or specularite banded with quartz to the extent that the average iron content is 30–35 per cent. Geologically these deposits possess a remarkable similarity to those of Sydvaranger; that of Fiskefjord is illustrated in Fig. 186. Other occurrences such as the small deposit at Smorten, illustrated in Fig. 187, and those of Jörendal, Madmoderen, etc., are of richer ore mixed in smaller amount with hornblende, biotite, augite, quartz, and felspar, like the occurrence at Solberg near Tvedestrand described by Vogt and Sjögren.[1]

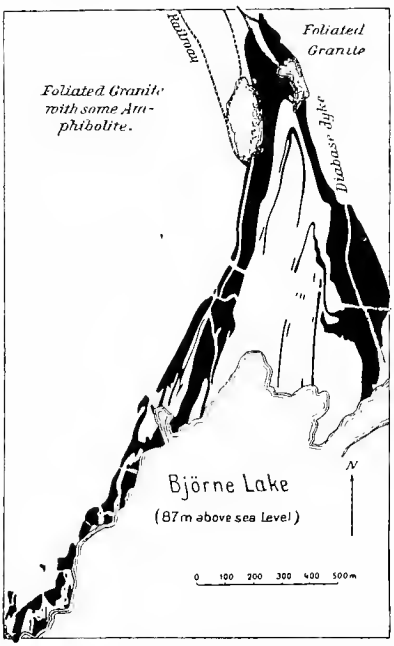

Fig. 185.—Map of the Björnevand (Bjorne Lake) district of Sydvaranger. Iron ore represented black.

The occurrences now being described, of which including the smaller ones there are thousands, all occur in foliated granite with which rock they are genetically closely related; they are not younger deposits hydrochemically formed after the solidification of the granite. The richer occurrences of the Solberg-Smorten type as well as the banded ores typically developed at Sydvaranger and Fiskefjord are occasionally traversed by younger or later granite dykes. The formation of the ore consequently took place in the magmatic stage of the granite. This, in connection with the absence of pneumatolytic and contact-metamorphic minerals,

[1] Vogt, 'Über magmatische Ausscheidungen von Eisenerz im Granit,' *Zeit. f. prakt. Geol.*, 1907; Hj. Sjögren, 'Über die Eisenerze im Granit auf Lofoten und die Parallelstruktur der gebänderten Eisendürrerze,' *Geol. Fören. Förh.*, 1908.

according to Vogt, suggests an origin by peculiar magmatic differentiation phenomena.

Typical representatives of both kinds of ore are found together in the

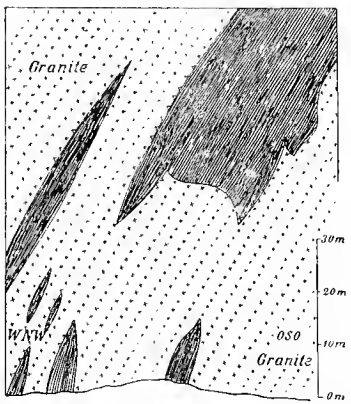

FIG. 186.—Quartz-banded iron ore in foliated granite. Section at Nedrevand near Fisketjord. Hinde. *Zeit. f. prakt. Geol.*, 1907, p. 88.

large granite area of Lofoten-Vesteraalen. The occurrence of rich magnetite-hornblende ore within the poorer banded ore of Sydvaranger also indicates that both kinds of deposits have broadly speaking the same origin. To what genetic processes however the difference in detail between the two ores is due cannot yet be said. From time to time with the

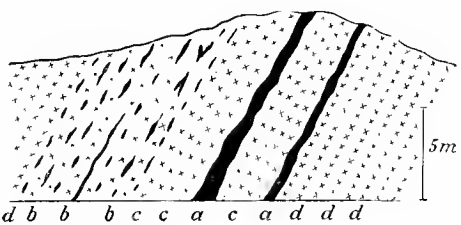

FIG. 187.—Section of iron ore in granite at Smorten, in the Lofoten Islands, showing magnetite (*a*), red granite with streaks of iron ore (*b*), schistose granite (*c*), and red granite (*d*). Vogt, *Zeit. f. prakt. Geol.*, 1907, p. 88.

deposits of the Solberg-Smorten type petrographical gradations between granite and ore occur, these gradations consisting of granite with varying amounts of magnetite, the *Eisengranitel* of Kjerulf and Dahll. The analogous gradations between granite and the banded quartz-magnetite have not yet been observed.

Hj. Sjögren in 1908 endorsed the view originally put forward by

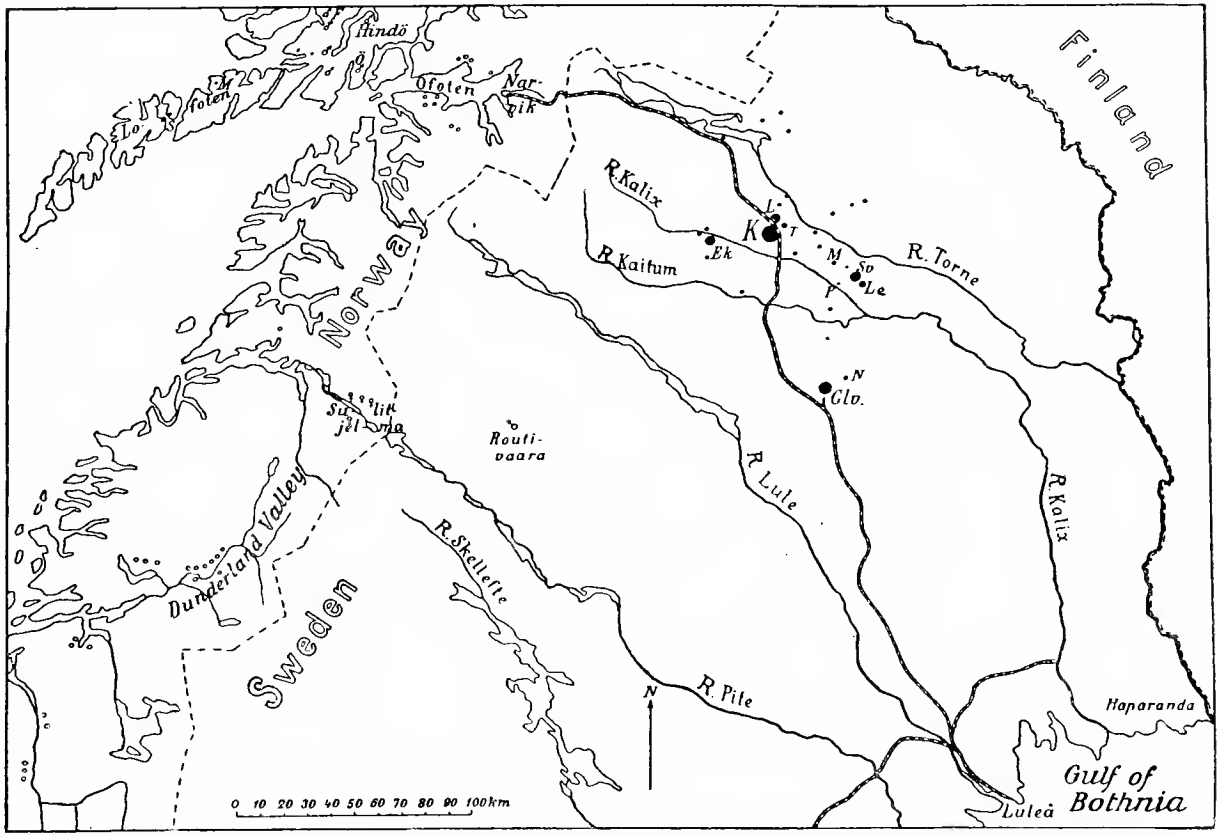

FIG. 188.—Map of the Norrbotten ironfield in Northern Sweden and the deposits in the adjoining portion of northern Norway.

In Norrbotten K=Kiirunavaara, L=Luossavaara, T=Tuollavaara, Ek=Ekströmsberg, Le=Leveäniemi, P=Painirova, Glv=Gellivare, N=Nautanen, copper ore. At Routivaara the deposit is one of titanomagnetite-spinelite. In Norway: in the granite of the Lofoten and of Hindö, the occurrences of rich ore are indicated by dots, and that of quartz-banded ore by iron symbols. S=Smorten, M=Madmoderen, F=Fiskefjord, Ö=Öksfjord. In addition, occurrences of magnetite-quartz schist and iron-mica schist which belong to the Dunderland type are indicated by small circles.

Vogt that the banded quartz-magnetite deposits in the Lofoten Islands were formed by magmatic differentiation. He regarded these ores as epigenetic deposits which previously to extrusion were concentrated in depth by differentiation within the magma. The ferruginous magmatic material kept in solution by the help of water and other solvents was then afterwards forced into the position it now occupies. For this procedure Sjögren, in analogy with the term diaschist, proposes the term diamagmatic.

It must here be remarked that the magmatic differentiation, as in the case of the chromite and titaniferous-iron deposits also, took place in many instances not where the deposits are now found but in depth, and that later an upward injection of the differentiated materials followed. Such magmatic streaks and lodes are in general to be regarded as differentiated lodes.[1] The newer name proposed by Sjögren appears therefore, and particularly for the quartz-banded ore, to be but little apt.

The previously mentioned titaniferous-iron deposits of Rödsand-Heindalen containing roughly 8 per cent of TiO_2, together with the banded quartz-magnetites and the rich iron- and apatite-iron ores free from titanium, all occur in granite areas, but with this important difference between them, that while the former are always bedded in amphibole- or in gabbro-schists, the latter occur right in the granite. This fact justifies the assumption that these latter have not passed through an intermediate stage in a gabbro-fractional-magma as have the occurrences at Rödsand, but that they, by strongly active differentiation, have separated directly from the granite magma.

Norrbotten in Northern Sweden

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[1] Compare the nomenclature of Brögger, *Die Gesteine der Grorudit-Tinguait-Serie*, 1894, p. 125.

Besides the enormous deposit Kiirunavaara-Luossavaara at Kiruna, the huge occurrence Gellivare, and the somewhat smaller deposits Ekströmsberg, Svappavaara, Leveäniemi, Mertainen, Tuollavaara, etc., many other smaller occurrences are found in Norrbotten, the most important of which are indicated in Fig. 188 by dots.

Within this ironfield both eruptive and sedimentary rocks occur. Among the first are found; granite with gneiss; a whole number of syenite varieties including syenite-porphyry, syenite-granulite; gabbro with diabase, etc.; while in places quartz-porphyry also occurs. Among the sedimentary rocks are found slates, quartzites, and conglomerates, which to all appearances are of Cambrian or perhaps of pre-Cambrian age. The rocks of the syenite group are in part older and in part younger than the Kiirunavaara conglomerate, this conglomerate being the most important of the sedimentary rocks. The deposits are mostly connected with syenite-

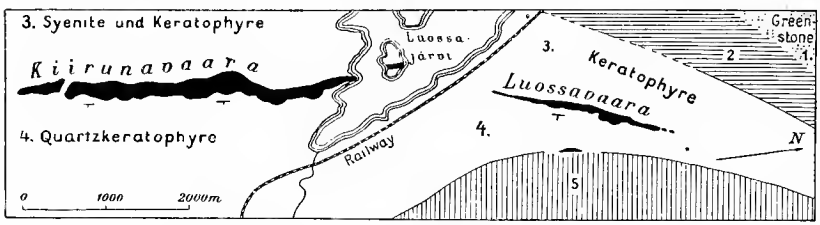

FIG. 189.—The iron deposits of Kiruna. P. Geijer, 1908.

1, Greenstone; 2, older sediments; 3, syenite and keratophyre; 4, quartz-keratophyre; 5, younger sediments.

porphyry, particularly with the varieties keratophyre and quartz-keratophyre, but also with syenite-granulite and granite-gneiss.

KIRUNA.—This deposit concerning its mass and metal content is unique. Although not absolutely unbroken, it nevertheless extends, as shown in Fig. 189, practically continuously for a length of about 8 km. In the immediate neighbourhood of the ore-body a number of sodium-syenite varieties occur, a quartz-keratophyre with 71 per cent silica forming the hanging-wall, and a keratophyre with 61 per cent forming the foot-wall. This latter rock towards the west passes over to a sodium-augite-syenite, with the augite almost completely altered to hornblende, the rock however still containing about 60 per cent of silica. In the hanging-wall beyond the quartz-keratophyre the so-called *Haukis* schists occur, these consisting of conglomerate, vesicular diabase, and quartzitic sandstone.

The ore-deposit itself consists chiefly of magnetite and subordinately of specularite; it also generally contains a considerable amount of fluor-apatite. Reckoning the amounts of Fe_2O_3, FeO, P_2O_5, and CaO together,

these make 96–98 per cent of the entire ore-body. The remainder consists of 1–2 per cent of SiO_2, 0·15–0·8 of TiO_2, 0·2–1·0 of Al_2O_3, 0·4–1·2 of MgO, 0·15–0·5 of MnO, 0·015–0·05 of S, etc. The magnetite is generally extremely fine-grained, very compact, and very hard. The apatite exists partly as microscopic crystals within the iron ore and partly as veins and streaks as much as and sometimes more than an inch in thickness, as

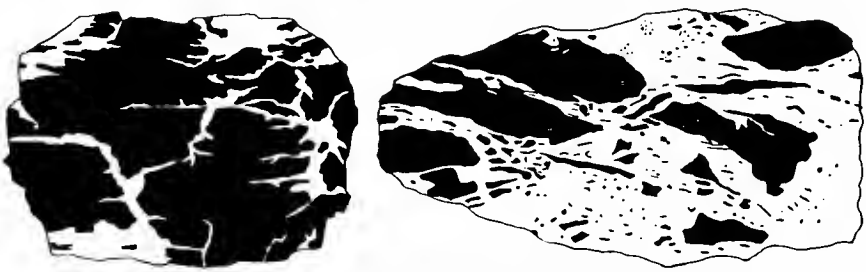

FIG. 190.—Streaks of apatite (white) in magnetite (black). Magnetite breccia in apatite. One-third natural size. Stutzer, 1907.

illustrated in Fig. 190. The deposit consists of two portions, the larger known as Kiirunavaara lying to the south, and the smaller known as Luossavaara to the north, with Lake Luossajärvi between. The length of the Kiirunavaara body upon land alone is 3·5 km. but if the continuation across the lake be included it is 4·75 km. The dip varies between 48° and 64° to the east, and the width between 28 m. and 145 m., this width being practically free from barren sections. At Luossavaara the ore-body has a length of about 1500 m. with a width of from 25 to 58 m., the

FIG. 191.—Section of the Kiirunavaara deposit through one of the summits of the range.

average dip being about 65° to the east. The outcrop at Kiirunavaara forms the back of an extended ridge, a section of which is given in Fig. 191; at Luossavaara it forms the summit of a rounded hill. This prominence of the deposit is explained by the greater resistance of the extremely hard and compact ore to atmospheric agencies, as compared with that presented by the rocks. The ridge at Kiirunavaara seen from a distance appears indented like a saw, with points which raise themselves one after the other to heights of 82, 178, 229, 248, 218, 179, 178, 206, 238, 239 and 207 m. respectively above the lake, which itself is about 500 m. above the

sea. In the depressions between these heights the width of the deposit is generally considerably smaller, a feature which by some investigators was regarded as indicating a decrease of width in depth. It is however more rationally explained by the greater success achieved by the forces of erosion where this resistant body was less wide.

The separation between the ore and its walls is generally very sharp, though in one place on the north-western slope of Kiirunavaara towards the lake, a breccia consisting of fragments of porphyry cemented by numerous veins of ore is observed. It is finally to be remarked that veins of apatite and ore, with tourmaline, zircon, quartz, etc., occur also in the hanging-wall porphyry east of Luossavaara, these veins according to

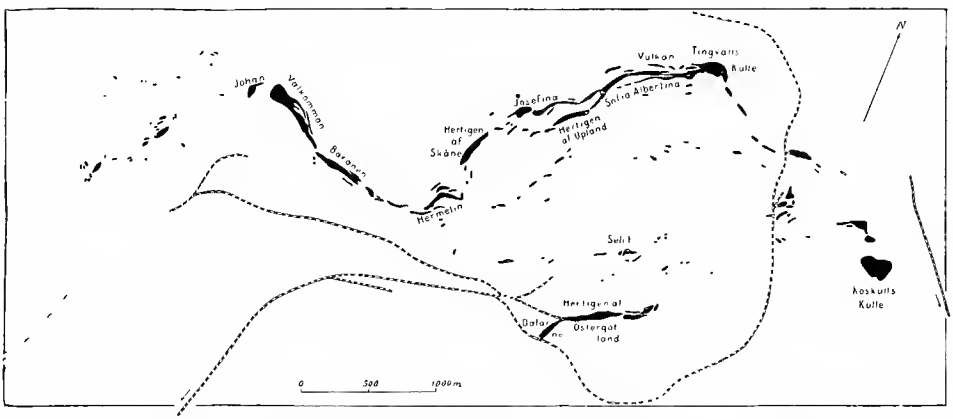

FIG. 192.—The deposits of the Gellivare district. *Jernkontorets Annaler*, 1906.

Geijer exhibiting fluidal structure. In the foot-wall porphyry again, cracks and cavities are found occupied by ore, hornblende, titanite, etc.

GELLIVARE.—In this district, 6–7 km. long and 2 km. wide, many larger and smaller deposits appear. The country-rock is a variety of gneiss, rich in felspar and generally red in colour, though hornblende-gneiss, biotite-gneiss, and sillimanite-gneiss also occur, the latter usually in actual contact with the ore. In close connection with these undoubted eruptive occurrences of gneiss, altered granite and granite-gneiss also occur, while dykes of granite-pegmatite traverse indifferently the gneiss, granite, and ore.

The ore-bodies are lenticular and conformably interbedded with the gneiss in which they occur. The largest among them have lengths from 250 to 500 m. or even exceptionally to 800 m., and horizontal extents from 3200 to 42,000 square metres. In addition there are many which are smaller than this and which possess only some 1000 square metres of horizontal extent.

The ore as a rule is fairly coarse-grained and in consequence of an alternating admixture with fluor-apatite, hornblende, augite, and mica, it appears streaked and banded. In some places corundum has been found, while fluorite, and zeolite have been established as rarities. The iron content is high and apatite is in most places present in considerable amount although the average phosphorus content is not quite so high as is the case at Kiruna. The iron ore, which is generally magnetite and less frequently specularite, constitutes together with the apatite 94–96 per cent of the mass, the remainder consisting of 2–3·5 per cent SiO_2, 0·2–0·5 TiO_2, 0·6–1·2 Al_2O_3, 0·4–1·0 MgO, and 0·03–0·06 per cent of sulphur.

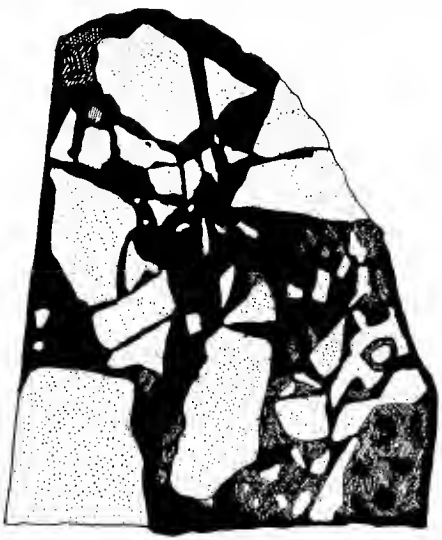

Fig. 193.—Ore breccia from Mertainen consisting of fragments of syenite-porphyry cemented by magnetite. W. Petersson.

The numerous other deposits in this district occur chiefly in syenite-porphyry and syenite-granulite. Similarly to Kiirunavaara and Gellivare these also are distinguished by a high iron content and by containing much apatite. In their geological relations too, they agree in most cases with those at Kiruna but with this difference, that the breccia found in places with some of the other occurrences is much more extensive in these. The deposit at Mertainen occurring in syenite-porphyry for instance is as a rule made up entirely of this breccia, veins of magnetite ramifying in all directions and enclosing fragments of the syenite-porphyry in the manner illustrated in Fig. 193.

The following table gives the particulars of the horizontal extent of these gigantic occurrences and the quantities of ore corresponding to one

metre of vertical depth, the deposits mentioned standing at a fairly high angle.

	Area of Horizontal Extent.	Quantity of Ore per metre of depth.
	sq. m.	tons.
Kiruna { Kiirunavaara	286,000	1,287,000
Kiruna { Luossavaara	25,000	112,500
Gellivare (excluding 60,000 sq. m. of poorer material)	185,000	550,000
Ekströmsberg	50,000	200,000
Svappavaara	50,000	190,000
Leveäniemi	32,000	128,000
Mertainen	10,000	40,000

The ore from Kiruna and Gellivare, according to the amount of phosphorus contained, is divided into the following principal classes, in addition to which there are a number of intermediate or sub-classes.

(*a*) *Kiruna.*

A-ore, with less than 0·05 per cent phosphorus and about 68 per cent iron.
B-ore, with a maximum of 0·10 per cent phosphorus and about 68 per cent iron.
C-ore, with a maximum of 0·60 per cent phosphorus and about 66 per cent iron.
D-ore, with from 0·75 to about 2·5 per cent phosphorus and from 60 to 66 per cent iron.
F-ore, with from 2 to 3 per cent phosphorus and from 55 to 60 per cent iron.
G-ore, with more than 2·5 per cent phosphorus and from 55 to 60 per cent iron.

(*b*) *Gellivare.*

A-ore, with less than 0·035 per cent phosphorus and about 68 per cent iron.
C-ore, with from 0·035 to 0·8 per cent phosphorus and from 62 to 66 per cent iron.
D-ore, with more than 0·8 per cent phosphorus and about 62 per cent iron.

Only a relatively small portion of the entire output of these two mountains of ore is low in phosphorus. The bulk from Kiruna contains 1·5–2 per cent and that from Gellivare about 1 per cent. Both mines therefore chiefly produce Thomas ore.

Concerning the quantity of ore probable at Kiirunavaara there has been much discussion. It was maintained by many that from the smaller width of the ore-body in the depressions in comparison with the greater width at the heights, and from the results of some bore-holes put down before the year 1898, that the ore in depth would fairly quickly disappear. Vogt in 1898 strongly opposed this view and it has since been proved, partly by other bore-holes and partly by magnetic survey, that this ore does in fact extend to considerable depth. The deposit indeed may be regarded as a magnetic wall striking north-south and dipping 60° to the east. The upper magnetic pole, according to the comprehensive magnetic work of V. Carlheim-Gyllensköld,[1] lies at a depth of approximately 100 m. below the outcrop, while from the course taken by the lines of

[1] *Jernkontorets Annaler*, 1907.

magnetic force the centre may be calculated to be about 1100 m. below this outcrop. The total extension in depth may therefore be estimated to be some 2200 m. Above the level of Lake Luossajärvi the quantity of ore in the combined occurrence Kiirunavaara-Luossavaara according to different estimates lies between 233 million and 292 million, or in round figures 250 million tons, and the total quantity to a depth of 300 m. below that level, 750 million tons. These figures may be compared with those previously given on p. 196 for the quantity of ore originally in the deposit.

From the opening of the Gellivare-Luleå railway, 211 km. long, in 1888 and up to and including the year 1908, 13·1 million tons of ore were shipped from Gellivare. Similarly, from the opening of the Kiirunavaara-Norvik line in 1902, and up to 1908, 8·4 million tons were shipped from Kiruna. The output for the year 1908 itself from Gellivare was 869,000 tons, while that from Kiruna was 1,649,851 tons. This latter corporation however has the intention to increase its output from and including the year 1916, to 3·2 million tons of ore containing 2 million tons of iron.

The genesis of these occurrences in Norrbotten has long been a disputed question, that of the deposits at Kiruna especially having provoked much discussion. According to the view formerly held in Sweden the porphyry was regarded as sedimentary hälleflinta and the ore as a sedimentary deposit. The eruptive character of this so-called hälleflinta was recognized however by Törnebohm in the year 1889. Some authorities, and among them more particularly Bäckström in 1898 and de Launay in 1903, considered the different occurrences of porphyry to be sheets and the ore to be younger than the porphyry in the foot-wall and older than that in the hanging-wall. The deposit was then regarded as sedimentary and the accretion of ore as having arisen by pneumatolytic processes from the igneous sheet in the foot-wall. Others considered the deposits to be of contact-metamorphic or even of metasomatic origin.

According to recent investigation, and especially that of Stutzer, the varieties of porphyry occurring in the immediate neighbourhood of the ore must be regarded not as sheets but as intrusions. As already mentioned, the porphyry to the west of the occurrence passes gradually over to the deep-seated rock, syenite. Stutzer, Geijer, and others, have shown that the ore is not only younger than the porphyry in the foot-wall but also than that in the hanging-wall. It must consequently be regarded as an intrusive occurrence. The breccia already mentioned as being found not only at Mertainen but also at Kiruna and Gellivare, is convincing evidence of this intrusive character. Further, the magnetite-apatite admixture of Kiruna and of the neighbouring deposits occasionally exhibits a fluidal structure such as can only be explained by its existence originally as a fluid magma. According to Stutzer the occurrences at Gellivare correspond

genetically with those at Kiruna, with this difference however that at Gellivare both the country and the ore have subsequently suffered intense metamorphism. To us a closer examination of this latter assumption appears however desirable. In any case reviewing all the evidence the conclusion is reached that both the Norwegian as well as the north Swedish iron deposits just described have been formed by processes of magmatic differentiation in acid eruptive magmas.

The occurrence at Solberg near Tvedestrand and the rich ore-bodies in the Lofoten Islands greatly resemble the A-ore of Gellivare, and between the apatite-iron of Lyngrot and that of Gellivare the mineralogical resemblance is equally remarkable. The apatite has in many cases, though certainly not in all, been concentrated by magmatic differentiation concurrently with the iron, an occurrence also met now and then in segregations of titaniferous iron. The titanic acid however which is so characteristic of these latter deposits is either entirely wanting in those in acid eruptives or occurs only in very small amount; at Gellivare and Kiirunavaara for example it seldom reaches more than 0·5 per cent. In this connection the enrichment of zircon at Solberg mentioned on p. 261 is genetically interesting.

While the above-described deposits of the Lyngrot-Solberg-Smorten and the Sydvaranger types occur in foliated granite fairly rich in potassium felspar and with at least 70 per cent SiO_2, the deposits of Kiruna among others in Norrbotten show a genetic dependency upon a magma which was more basic and which contained relatively more sodium.

It is probable that the magmatic segregations in acid eruptive rocks such as have just been described are both in distribution and number much more extensive than would appear from the literature on the subject. The very important deposit of Grängesberg in Middle Sweden which contains about 62 per cent of iron and 1 per cent of phosphorus, and the much smaller occurrence at Nissedal in Norway with 58–60 per cent of iron and about 1·75 per cent of phosphorus, exhibit in many ways so pronounced a resemblance to the deposits at Gellivare and Lyngrot that they probably have the same genesis. Again, the banded quartz-magnetite ore of the Sydvaranger type is identical in structure with the so-called *Torrsten* or lean ore of Striberg and other mines in Middle Sweden. On these grounds among others, some Swedish investigators, and especially H. Johannsson and Hj. Sjögren, have come to the conclusion that the deposits of Grängesberg, Striberg, Norrberg, Persberg, Dannemora, etc., in Middle Sweden were originally formed by magmatic processes subsequently to which they suffered intense alteration. According to their view two principal phases may be distinguished in these occurrences, namely, the primary formation and the secondary alteration.

The genesis of these Swedish occurrences, which include such divergent types as Grängesberg on the one hand and Dannemora on the other, appears nevertheless to be far from clear. Some of them may be of magmatic origin, belonging therefore to the group of deposits now under description, while others appear obviously to have been formed otherwise. On account of this uncertainty as to their genesis these deposits in Middle Sweden, which it has been the custom to regard as all of one group, will as such be treated together in a later section.

From the recent description by Newland,[1] it would appear that several of the deposits of titanium-free magnetite of the Adirondacks in the United States are probably closely related to the above-described Scandinavian occurrences in granite or other acid eruptive rock. The Adirondack deposits, some of which have large dimensions, occur in foliated granite or in acid eruptive gneiss. They are sometimes low in phosphorus, though sometimes they contain up to 2 per cent, corresponding to 10 per cent of apatite. They are consequently typical apatite-magnetite deposits. The iron content is high, 60–70 per cent, while the limit of payability is 35 per cent. Quartz, felspar, pyroxene, hornblende, etc., occur as gangue. The form of the deposit is tabular like that of those in Scandinavia. Granite-pegmatite often occurs as country-rock.

Newland mentions more than once the occurrence of gradations between the deposit and the rock and comes to the conclusion that the ore presumably has arisen by differentiation within an acid eruptive magma. The admixture of apatite, hornblende, fluorite, etc., he believes however to have resulted from pneumatolytic or pneumatohydatogenetic processes. It is more probable however that these minerals, with the possible exception of fluorite, were also formed by magmatic differentiation. A closer comparison between these deposits and those of Scandinavia described above would it is thought afford much help in solving the genesis of the entire group.

The well-known iron deposits of Wyssokaia-Gora and Goroblagodat, in the Urals, have also been regarded by some investigators as magmatic segregations in syenite. These deposits however possess so many properties common to contact-metamorphic deposits that it is preferable to describe them under that group.

Occurrences of Rutile in Granite

Of more than ordinary interest are the strikingly related occurrences of rutile in granite at Kragerö in Norway, and at Roseland in Virginia, which have lately been described by W. C. Brögger [2] and by J. L. Watson.[3]

[1] D. H. Newland, *Econ. Geol.* II., 1907.

[2] *Ges. d. Wiss.*, Christiania, December 2, 1903. [3] *Econ. Geol.* II., 1907.

In the first mentioned occurrence the rutile is accompanied by a moderately acid plagioclase, forming a rock which Brögger terms 'krageröite' and which generally contains 10–50 per cent of rutile. It occurs streak-like in foliated granite in the neighbourhood of an enormous dyke of granite-pegmatite on one side, and of olivine-hyperite with amphibolite on the other, both of which are traversed by apatite-rutile veins. At Roseland the rutile deposits, usually containing 10–30 per cent of rutile together with felspar, quartz, and occasionally also some ilmenite, occur likewise in granite, which in part is foliated. Here also they are found with dykes of granite-pegmatite on one side and with diabase and gabbro on the other. In both cases the rutile is a magmatic product formed during consolidation, though whether it became assembled by magmatic differentiation or was introduced by pneumatolytic processes cannot yet be said. These two deposits supply the present demand for rutile which amounts to some hundreds of tons per year.

B. THE SULPHIDE SEGREGATIONS

At ordinary furnace temperatures, 1200°–1700° C., molten silicates and sulphides show a limited mutual solubility. Upon fusion, slag and matte separate from one another though not completely; on the one hand the sulphides hold a very small amount of silicate in solution, while on the other the silicates hold some sulphide, having the formula RS, where R=Fe, Zn, Mn, Ca, etc. The solubility of sulphides in silicates varies with the different sulphides. All other conditions being equal and particularly that of temperature, this solubility is materially greater in basic silicates, that is those rich in FeO, ZnO, MnO, CaO, than in those which are acid.

The effect of temperature is to markedly increase the solubility. In the neighbourhood of 1500° C. basic slags can take up as much as 7–9 per cent of MnS, ZnS, or (Zn, Fe)S, in solution; with FeS and CaS the solubility is somewhat less; while with NiS, CoS, PbS, Cu_2S, and Ag_2S, it is very small.[1] At the cooling of such molten silicates the minerals sphalerite, ZnS or (Zn, Fe)S; alabandite, MnS; and CaS, crystallize early, while the separation of FeS on the other hand appears only to commence later. If the mutual solubility of two fused masses rises with the temperature it must often be the case when this is sufficiently high that the composition of the two masses is the same, that is to say, complete mixing will have taken place. Since also according to experience the solubility of sulphide in molten silicate rises markedly with the temperature it may be assumed

[1] Vogt, *Silikatschmelzlösungen*, I., 1903.

that silicate and sulphide at the very high temperature which will exist in the heated magmas of the earth's interior, will completely mix, and original magmas in consequence must be assumed to hold a considerable amount of sulphide in solution.

To illustrate the separation of the sulphide in solution from an original highly-heated molten silicate rich in sulphur the most simple case may be taken where but two components *a* and *b* are present. In Fig. 194 the

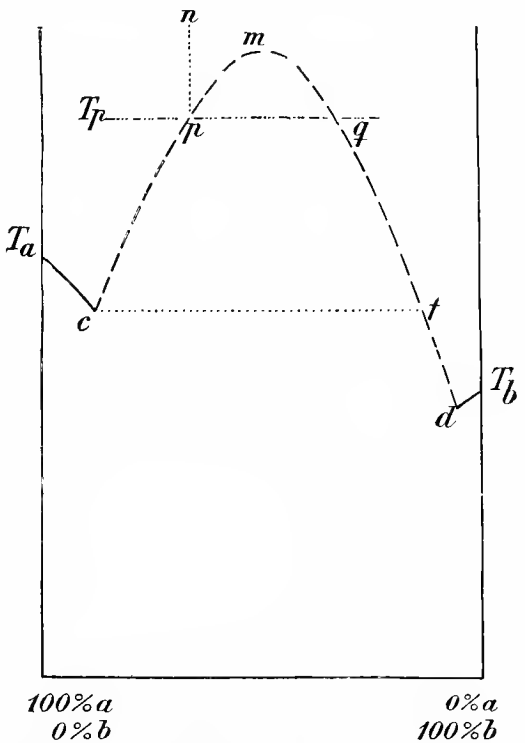

FIG. 194.—Diagram explaining the separation of a sulphide from a molten silicate magma.

percentage relation between these two components is represented by the abscissae ; the ordinates represent the temperature. T*a* and T*b* are the melting points of *a* and *b* respectively. The curve *cpmqfd* is that of the solubility for a binary magma with limited mutual solubility. T*a* to *c* and T*b* to *d* are the curves of solidification.[1] With an original highly-heated molten silicate of the composition *n*, *a* and *b* are completely soluble in one another. Upon cooling to temperature T*p* however the separation

[1] Compare Fig. 56 of *The Natural History of Igneous Rocks*, by Alfred Harker. London, 1909.

into two fused materials begins, one being p consisting in greater part of a with some b, and the other q consisting in greater part of b with some a. With further cooling the separation becomes more pronounced until at one stage two fused materials of composition c and f appear. From that designated c the component a crystallizes with simultaneous crystallization of some of the material f. This material in cooling further follows the curve fd with crystallization of some of the material a, till finally the material d solidifies with simultaneous crystallization of a and b.

The separation of sulphide magma from silicate magma is however most certainly not so simple as in the above illustration, since each may consist of a whole number of components, and the fusion points of some sulphides vary considerably from those of others. The composition of clean nickel-pyrrhotite from Sudbury for instance or of pyrite from Huelva or Röros appears according to Vogt to indicate that the final crystallization of the sulphides took place from molten solutions, which still contained one or two per cent of silicates, the composition of such pyritic masses being similar to that at point d in the above-mentioned Fig. 194. In addition it must also be remarked that fused sulphides, such for instance as the mattes of iron, copper, nickel, lead, etc., are very fluid or in any case are much more fluid than even the most fluid silicates. They may therefore find their way into the smallest cracks or fractures of the country-rock to form there the so-called intrusive lodes and fahlbands.

(1) The Nickel-Pyrrhotite Group

Nickel-Pyrrhotite Deposits in Gabbro.

LITERATURE

J. H. L. Vogt. Articles in the *Zeit. f. prakt. Geol.*, 1893, cited on p. 242.

The numerous nickel-pyrrhotite deposits found in different countries, and especially in Canada, Norway, Sweden, Pennsylvania, in the Monte Rosa district of Piedmont, etc., in their mineralogical and geological relations form a sharply-defined group. The most important characteristic common to them all lies in their occurrence within or at the margins of gabbro masses, chiefly norite, or exceptionally in the volcanic rocks corresponding to this plutonic rock. To this characteristic must be added the mineralogical and chemical simplicity of the ore and the gangue.

Geological Position of the Deposits.—Of about 50 nickel-pyrrhotite occurrences distributed over Norway the greater number occur in fresh unaltered norite which often carries diallage, sometimes olivine, and at other times quartz, the latter association forming quartz-norite. Some

of them however occur in gabbro more or less greatly uralitized, the pyroxene being so completely altered that the rocks were formerly regarded as gabbro-diorite and later as uralite-gabbro. The term gabbro in this connection must therefore be regarded as a collective name since it cannot be decided whether the original rock was gabbro in the strict sense of that term, that is with monoclinic pyroxene, or norite with rhombic pyroxene. The same petrographical characteristics also hold good for the more important of the Swedish deposits. Similarly at Varallo on the south slope of Monte Rosa the deposits occur in norite which sometimes contains olivine but at other times does not. The nickel-bearing rock at Sudbury in Canada is also an occurrence of norite which usually contains a small percentage of quartz but which, though agreeing with some of the Scandinavian occurrences in regard to its silica content, is somewhat more acid than the rock enclosing the nickel occurrences in the majority of cases there.

The variety of gabbro which favours the nickel-pyrrhotite deposits is therefore one which carries hypersthene. Occurrences in diallage-gabbro are more rare, though such do occur, as for instance in the olivine-diabase of Lundörren in Sweden and in the hornblende-olivine-diabase of Sohland in Saxony, etc. In by far the greater number of cases in Canada, Norway, and Sweden, the gabbro is of Archæan age. Sometimes in Norway however it intrudes regionally-metamorphosed Cambro-Silurian rocks and the intrusion presumably occurred in connection with orogenic movements of Devonian age.

It is characteristic of these nickel deposits that in their immediate neighbourhood a number of segregations of basic or ultra-basic rock occur. With many of the occurrences in Norway, as for instance with those at Erteli, Espedal, Höiaas near Tvedestrand, Nonaas in Hosanger, Senjen, as well as at Varallo in Italy, there are occurrences of bronzite-amphibole-olivinite or amphibole-picrite close to the deposits. Similarly at Romsaas in Norway, as illustrated in Fig. 202, segregations of a spherical norite containing 80 per cent of bronzite, hornblende, and mica, are found. It is also reported from Sudbury that the norite in immediate proximity to the deposits is more basic than at a distance.

Further the gabbro is often crossed by acid leucokratic streaks and dykes, between which and itself the intermediate stages marking a gradual passage from one to the other may often be recognized, even though these acid inclusions may have a granitic composition. Upon these and other grounds the conclusion may be drawn that these acid streaks and dykes have arisen by differentiation within the gabbro magma, a differentiation in the acid anchi-eutectic direction. They are found in several Norwegian mines, as for instance at Flaad in Evje and at Skjäkerdalen, in considerable extent and in close connection with nickel deposits.

Mineralogy and Chemistry of the Deposits.—The most important ores are pyrrhotite, pyrite, and chalcopyrite. Analyses of apparently clean pyrrhotite from deposits in gabbro, collected from the most varied geographical distribution, have given 2–5 per cent of nickel and some cobalt. In some cases these two metals together have been responsible for 8–12 per cent of the mass but only when by chance the mineral pentlandite has been present. On the other hand the pyrrhotite occurring with the fahlbands in the gneiss of the crystalline schists in Norway, Sweden, the Erzgebirge, Canada, etc., generally contains a much lower amount, some 0·2–0·5 per cent of nickel and cobalt together. Herein lies an essential and extremely characteristic difference between the pyrrhotite of the two different classes of deposits. It was formerly thought that the nickel and cobalt content of these pyrrhotite deposits was associated with the constitution of that mineral, in that the chemical place of a small amount of the iron content was actually taken by these two allied metals. This view however is not correct. With many of the occurrences in Norway, Sweden, and Canada, the mineral pentlandite may be recognized even with the naked eye as the vehicle of the nickel.[1] This mineral is the compound (Fe, Ni)S, sometimes with 22 per cent of nickel corresponding to the proportion 2 Fe : 1 Ni; at other times with about 34 per cent corresponding approximately to 1 Fe : 1 Ni, some cobalt in addition being always present. It is known to be non-magnetic. In the treatment of apparently quite clean pyrrhotite from different mines in Sudbury, Ch. W. Dickson[2] from the powdered material was able to magnetically separate a magnetic portion with but a low nickel content from a non-magnetic portion which contained about 34 per cent, a percentage which corresponds almost exactly to the formula (Fe, Ni)S. In addition, W. Campbell and C. W. Knight[3] working on metallographic lines demonstrated the presence of microscopically fine pentlandite intergrown with pyrrhotite and chalcopyrite in samples of pyrrhotite from various occurrences in Canada, Norway, Sohland in Saxony, and from the Gap mine in Pennsylvania. By these investigations it is established that the preponderating amount of nickel in pyrrhotite is accounted for by the admixed pentlandite; whether in addition a smaller nickel and cobalt content enters into the constitution of the pyrrhotite remains still an open question. Extensive technical research has been undertaken to discover a satisfactory means of separating magnetically and on a large scale the embedded pentlandite from the pyrrhotite. Since however the former mineral only occurs in very fine particles, the finest grinding is necessary or considerable loss of nickel occurs.

[1] Scheerer, *Poggendorffs Annalen*, Vol. 58, 1843; Vogt, *Geol. Fören. Förh.*, 1892; Penfield, *Am. Jour. Sc.*, 1893.

[2] *Trans. Am. Inst. Min. Eng.*, Feb. 1903.

[3] *Eng. and Min. Jour.*, Nov. 17, 1906.

In addition to pentlandite, some polydymite, Ni_3FeS_5, is also occasionally found in some Canadian mines.[1] Millerite, NiS, also occurs, this mineral having been found in Canada, in the Gap mine of Pennsylvania, as well as in other mines, though it is however generally regarded as a secondary product.

An average sample from a number of Norwegian and Swedish mines would give generally 1 Co to 8–15 Ni, while with the Canadian deposits a ratio of approximately 1 : 40 has been established.

Ordinary pyrite occurs here and there in preponderating amount, though this is seldom the case. Generally it is scarce and where occurring is found as idiomorphic crystals embedded in pyrrhotite or chalcopyrite. Such crystals in some Scandinavian deposits contain relatively much cobalt and but little nickel, the relation for example may in some cases be 10–12 Co : 1 Ni, whereas in the surrounding pyrrhotite it would be 0·08–0·16 Co : 1 Ni.[2]

The proportion between the chalcopyrite and the nickel-pyrrhotite plus pyrite varies in different occurrences only between narrow limits. Generally there is about fifteen times as much pyrrhotite plus pyrite as chalcopyrite. Average samples of ore from Scandinavian mines give 1 Cu : 1·3–2 Ni, while those from Canada contain 1 Cu : 0·8–1·5 Ni. This proportion however may vary in different parts of one and the same deposit; it has indeed been observed both in Canada and in Scandinavia that the chalcopyrite is more abundant in the outer portions than in the centre of a deposit. The texture and aggregation of the ore is usually such that the chalcopyrite can only in part be separated by hand; more generally it is so finely distributed that it must be treated with that portion smelted for nickel. Several of the deposits here described indeed were in former years exploited for the copper they contained.

Magnetite and titaniferous magnetite are often found in nickel-pyrrhotite deposits, samples of the latter mineral from the Murray mine, Sudbury, containing 18·35 per cent of TiO_2. Marcasite, cobaltite, danaite, annabergite, gersdorffite, bornite, galena, sphalerite, and molybdenite, have been found as mineralogical curiosities in some deposits, though always only in small amount. It is characteristic of the entire group that the most common ores such as galena and sphalerite are almost always completely absent. In the nickel matte formed when these ores are smelted it is usually the case that not even traces of lead, zinc, arsenic, antimony, or bismuth, can be detected; on the other hand the presence of the platinum metals in very small amount, and of gold and silver, may be

[1] Clarke and Catlett, *Am. Jour. Sc.*, 1889.
[2] Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 270.

regarded as characteristic. The rare arsenide of platinum, sperrylite, $PtAs_2$, as is well known, was first discovered in the weathered outcrop of one of the Sudbury mines.[1] Small amounts of platinum and other platinum metals, of gold, and of silver, as already stated on p. 155, have been established in nickel ore in Canada, Norway, and Sweden.[2]

Morphology of the Deposits.—Gabbro according to numerous analyses usually carries 0·1–0·25 per cent of sulphur, corresponding to 0·2–0·5 per cent of sulphides, pyrrhotite or pyrite, which minerals are to be regarded as primary though accessory constituents of the rock. Within an occurrence of gabbro it is often the case that in some parts the sulphide content is considerably higher, reaching 2–5 per cent of the mass, a figure which may less frequently rise to 10 or even 30 per cent without disturbing the proportion between the plagioclase and the unaltered pyroxene constituents of the rock. Since in this case the pyritic gabbro in its structure still resembles the normal rock poor in sulphide, petrographically it can only be regarded as a variety of that rock. It corresponds therefore to the ilmenite- or titanomagnetite-gabbro, -norite and -pyroxenite, and by Vogt has consequently been termed pyrrhotite-gabbro, a name which has since been adopted by many other authorities. During the nickel boom in the 'seventies many mines in Norway started to work such pyrrhotite-norite or pyrrhotite-gabbro containing only some 30 per cent of these sulphides.

With those deposits where the sulphides are greatly concentrated the petrographical nature of the ore is more complicated and often somewhat variable in different deposits. Such occurrences also are often to be regarded chiefly or entirely as pyrrhotite-gabbro, even when containing some 50–75 per cent of such sulphides. In many cases the mass is practically one of clean sulphides, pyrrhotite, pyrite, and chalcopyrite, while a breccia structure may often be observed both on a large and small scale. This structure arises when fragments of the country-rock, normal gabbro or pyrrhotite-gabbro, are surrounded by solid sulphide. Moreover sulphide veins are often seen to traverse the country-rock, one such vein of a larger size being illustrated in Fig. 16, while the ramification of such veins on a smaller scale along the cracks and cleavage-planes of the other constituents of the gabbro is illustrated in Figs. 195 and 196. It must also be remarked that particles of almost clean sulphide are not only occasionally associated with the ordinary minerals of the gabbro but also with quartz, which material is then present even to the

[1] Penfield and Wells, *Am. Jour. Sc.* XXXVII., 1889; *Zeit. f. Krist. Min.* XV., 1889.

[2] F. W. Clarke and C. Catlett, *Am. Jour. Sc.*, 1889; T. L. Walker, *ibid.*, 1896; C. W. Dickson, *ibid.*, 1903; Vogt, *Zeit. f. prakt. Geol.*, 1902; F. M. Stapff, *Berg- und Hüttenm. Zeit.*, 1858.

extent of being more abundant than the quartz in quartz-norite. The leucokratic streaks and dykes described above as occurring in some mines, also occasionally carry some pyritic sulphide as an accessory constituent of their mass.

The nickel-pyrrhotite deposits in by far the greater number of cases occur in the peripheral portions of a gabbro mass, and often actually at the contact of the gabbro with the country-rock, especially if that be gneiss, mica-schist, foliated granite, etc., this situation being illustrated in Figs. 198–201, 203, and 204. In these cases the separation between the pyritic mass and the gneissic country-rock is usually fairly clean, whereas, as illustrated in Fig. 197, in the direction of the gabbro on the other hand, a gradual transition through pyrrhotite-gabbro with decreasing amounts

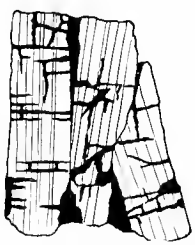

Fig. 195. — Plagioclase crystals from the pyrrhotite-gabbro of the Flaad mine in Norway, traversed by pyrrhotite veins. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 139.

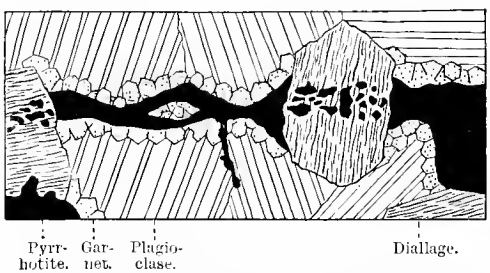

Fig. 196.—Pyrrhotite-gabbro from the Erteli mine, Norway, showing pyrrhotite veins fracturing the felspar and partly dissolving the diallage in their course. The pyrrhotite at the contact with the plagioclase is bordered with a garnet zone. Magnified 120 times. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 139.

of sulphide takes place. At times also the country-rock in the neighbourhood of the contact is so traversed or impregnated with the sulphide that it is mined and smelted. In Norway occurrences are known, at the Ringerike mines for instance, where a finely-foliated gneiss in immediate contact with the norite has been so impregnated with pyrrhotite, pyrite, and chalcopyrite, as to present the appearance of a fahlband in the gneiss. In one small mine indeed this 'fahlband' and the poorer norite were worked.

The deposits occurring at the contact of gabbro with gneiss, etc., are generally most irregular in form, and the width of the deposit may vary greatly even between two places quite close together. In depth however it is the experience that many of these deposits maintain their dimensions better. Deposits which occur in the central portion of a gabbro mass, as for instance that at Klefva in Sweden, are less common. In that mine several irregular though extensive streak-like lodes are worked. In this

connection reference is made to Fig. 202 showing the occurrence at Romsaas in Norway, and to Figs. 204 and 205 illustrating that at Flaad in the same country.

Genesis of the Deposits.—As suggested more particularly by Vogt in 1893 [1] the nickel-pyrrhotite deposits are to be regarded as magmatic segregations in gabbro or in chemically analogous volcanic rocks. The following points speak for such an origin :

1. The connection of the numerous deposits in different countries with occurrences of gabbro or exceptionally with the volcanic representative of that deep-seated rock, is constant and regular.

2. The several occurrences so resemble one another not only geologically but also mineralogically that they must be of the same genesis

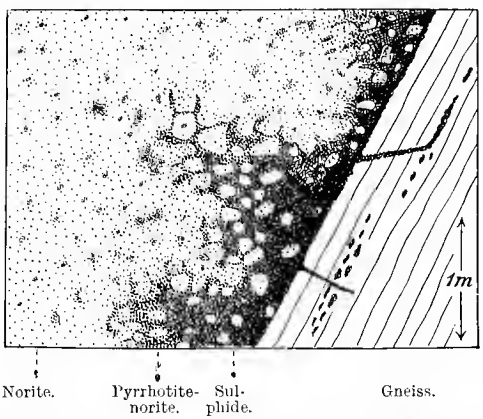

FIG. 197.—Section on a large scale of the occurrence in the Meinkjär mine, Norway, further illustrated in Fig. 201. Vogt, *Zeit. f. prakt. Geol.*, 1893, p. 137.

throughout, while the unvarying character of the deposits postulates a simple process of formation.

3. Gradations between ore and gabbro through the intermediate stage of pyrrhotite-gabbro are often to be observed and therefore the ore essentially must have been formed in a similar manner to that rock.

4. The structure of the clean or almost clean sulphide mixture with idiomorphic crystals suggests crystallization from a single magmatic solution and not from several solutions following one another as was evidently the case for example with the lead-silver-zinc lodes.

5. The deposits often occur in those parts of a gabbro mass which are distinguished by pronounced magmatic differentiation of the eruptive rock.

[1] *Op. cit.* ; also *Geol. Fören. Förh.*, 1891, p. 529 ; 1892, p. 321 ; *Zeit. d. D. Geol. Ges.*, 1891, p. 819.

6. The deposits are sometimes crossed by dykes of basic rock, diabase, olivine-diabase, etc., which are to be regarded as later effusions of the same eruption of gabbro. The formation of the ore belongs therefore to the magmatic period of the rock in which it occurs. Such dykes are illustrated in Fig. 200.

7. Some of the deposits are traversed and accompanied by acid leucokratic streaks and dykes which represent the acid segregation products from the gabbro-magma, from which also it follows that the formation of the deposits took place during the magmatic period of the eruptive rock.

8. The characteristic presence of titanomagnetite allows a manner of formation analogous to that of the magmatic titaniferous-iron deposits to be postulated.

9. Pneumatolytic minerals are completely wanting.

10. The minerals usually formed in the wet way are not present as part of the primary formation.

In addition to these points, others such as arise from observation in particular cases are quoted later.

By this theory the peculiarities of this group of deposits are explained. Concerning the characteristic presence of nickel, cobalt, and copper, it follows from the constant association of these deposits with basic eruptive rocks that these metals must be derived from such rocks. Since also the ore according to the theory here presented is of magmatic origin the nickel, cobalt, and copper contained, must be traced back to that period. It may well be that a sulphide, RS, dissolved in the magma, has been the means of effecting the transfer of these metals from an original combination with silica to one with sulphur, thus, $RS + NiO \,.\, (Fe, Mg, Ca, \ldots)O \,.\, mSiO_2 = NiS + RO \,.\, (Fe, Mg, Ca, \ldots)O \,.\, mSiO_2$. The basic rocks admittedly are distinguished in general by the presence of nickel, cobalt, and copper, in small amount. It is just these metals which are the most readily converted to sulphide, Fournet's sequence in this connection being Cu, Ni, Co, Fe, Sn, Zn, Pb, Ag, Sb, and As. The occurrence of the platinum metals in magmatic deposits, for instance metallic platinum in peridotite, and a low platinum content in nickel-pyrrhotite, etc., has already been mentioned on p. 155.

The disposition of these pyrrhotite occurrences in the marginal portions of eruptive masses is analogous to many other phenomena of magmatic differentiation. The fractional magmas which separating from one another finally give rise to dykes of varied composition, move as they are formed in the direction of the cooling surfaces and there collect. The corundum deposits mentioned on p. 250 as occurring along the margins of some peridotite masses, are illustrative of this. At times, though seldom the case, pyrrhotite-gabbro occurs within the gabbro and more or

less removed from the periphery. Such an occurrence probably resulted when a magma, rich in sulphide, collected originally near the periphery, became pressed upwards in abnormal eruption. The occurrence of dykes or streaks of pyrrhotite-gabbro, often cleanly separated from the country-rock, of the breccia described above, and of the sulphide veins in gabbro and country-rock, may be explained as the result of local eruption or intrusions formed by the sulphide or the sulphide-silicate magma. The extremely fine sulphide veins in the cracks and cleavage planes of the accompanying minerals, illustrated in Fig. 195, are explained by the fluidity of the fused sulphide.

Not infrequently these peripheral deposits are so bedded that the foot-wall is of gneiss and the hanging-wall of gabbro, or *vice versa*, cases of this at Sudbury, Canada, and at Meinkjär, Norway, being illustrated in Figs. 197, 200, and 201. This has been explained both in Canada and Norway by the sinking of the heavier sulphide components as they separated from the silicates.

According to the theory which has here been developed it follows that small gabbro masses can only contain small deposits and that the large occurrences are exclusively in connection with extensive areas.

The enrichment of chalcopyrite often to be observed especially in the peripheral portions of the nickel-pyrrhotite occurrences must result from a separate magmatic differentiation within the sulphide magma itself. A similar occurrence is found with the pyritic sulphide deposits to be described in the next section.

Independently of Vogt, both A. E. Barlow and R. Bell in 1891, and H. B. von Foullon in 1892, urged a molten origin for the nickel-pyrrhotite deposits, though without developing any comprehensive discussion or demonstration. Since the appearance of the article by Vogt in 1893 the genesis of these deposits has been the subject of repeated discussion. Most authorities who have concerned themselves with the question, particularly F. D. Adams, A. E. Barlow, D. H. Browne, A. P. Coleman, J. F. Kemp, and T. L. Walker, for Canada and the United States; for Norway and Sweden all the more recent authorities; and B. Lotti for Varallo in Italy, now endorse this theory of magmatic formation.

Admittedly there are a large number who oppose its acceptance. Posepny in his treatise upon the genesis of ore-deposits [1] declared the theory to be a chemical impossibility and denied the solubility of sulphide in silicate. Several other authorities as E. Weinschenk,[2] R. Beck,[3] H. W.

[1] Engineering Congress, Chicago, 1893; *Berg- und Hüttenm. Jhrb. der Bergakad., Leoben Pribram*, etc., XVIII., 1895.

[2] 'Die Nickel-Magnetkieslagerstätten zu St. Blasien im Schwarzwald,' *Zeit. f. prakt. Geol.*, 1907.

[3] 'Die Nickelerzlagerstätten von Sohland in Sachsen,' *Zeit. d. D. Geol. Gesell.*, 1903.

Hixon[1] and C. W. Dickson,[2] have on the other hand argued a secondary aqueous deposition of the ore. Stress is laid upon evidence which would show that the accretion of ore took place after the deformation of the enclosing rock, and especially after the deformation of the primary pyroxene minerals to actinolite, chlorite, talc, etc. This view however does not agree with all the facts. Nickel-pyrrhotite is often found, both at Sudbury and in Norway, etc., in norite which is quite fresh and in which the hypersthene is unaltered.[3] There can therefore be no question of the uralitization of the gabbro in general before or contemporaneously with the deposition of the ore. In places the sulphide-bearing gabbro has subsequently been decomposed, though in general no genetic connection between this decomposition and the formation of the ore can be demonstrated. Moreover, the characteristic peculiarities of the nickel-pyrrhotite deposits as enumerated on pp. 286 and 287, cannot be explained by a hydrothermal process.

Some investigators, including Vogt in 1883,[4] suggested a combination of magmatic segregation with pneumatolysis, according to which metalliferous vapours evolved from the magma in one place were decomposed in another, depositing the ore in rock already consolidated. This theory again does not however explain the characteristic properties of these deposits.

Sudbury in Canada

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The mining district of Sudbury lies in the northern portion of Ontario and on the north side of Lake Huron. It has a length of about 60 km. in a south-west and north-east direction, a width of from 25 to 30 km., and as shown in Fig. 198 it is crossed by the Canadian Pacific Railway. The eruptive rocks present consisting of quartz-norite and granite form an irregular field of basin shape, illustrated in Figs. 198 and 199. The

[1] Upon Sudbury, *Can. Mg. Inst.* IX., 1906.

[2] Upon St. Stephen in New Brunswick, Sohland and Sudbury, *ibid.*, 1906; *Can. Mag. Rev.*, 1906.

[3] A. P. Coleman, *Zeit. f. prakt. Geol.*, 1907, p. 221.

[4] *Geol. Fören. Förh.*, 1883.

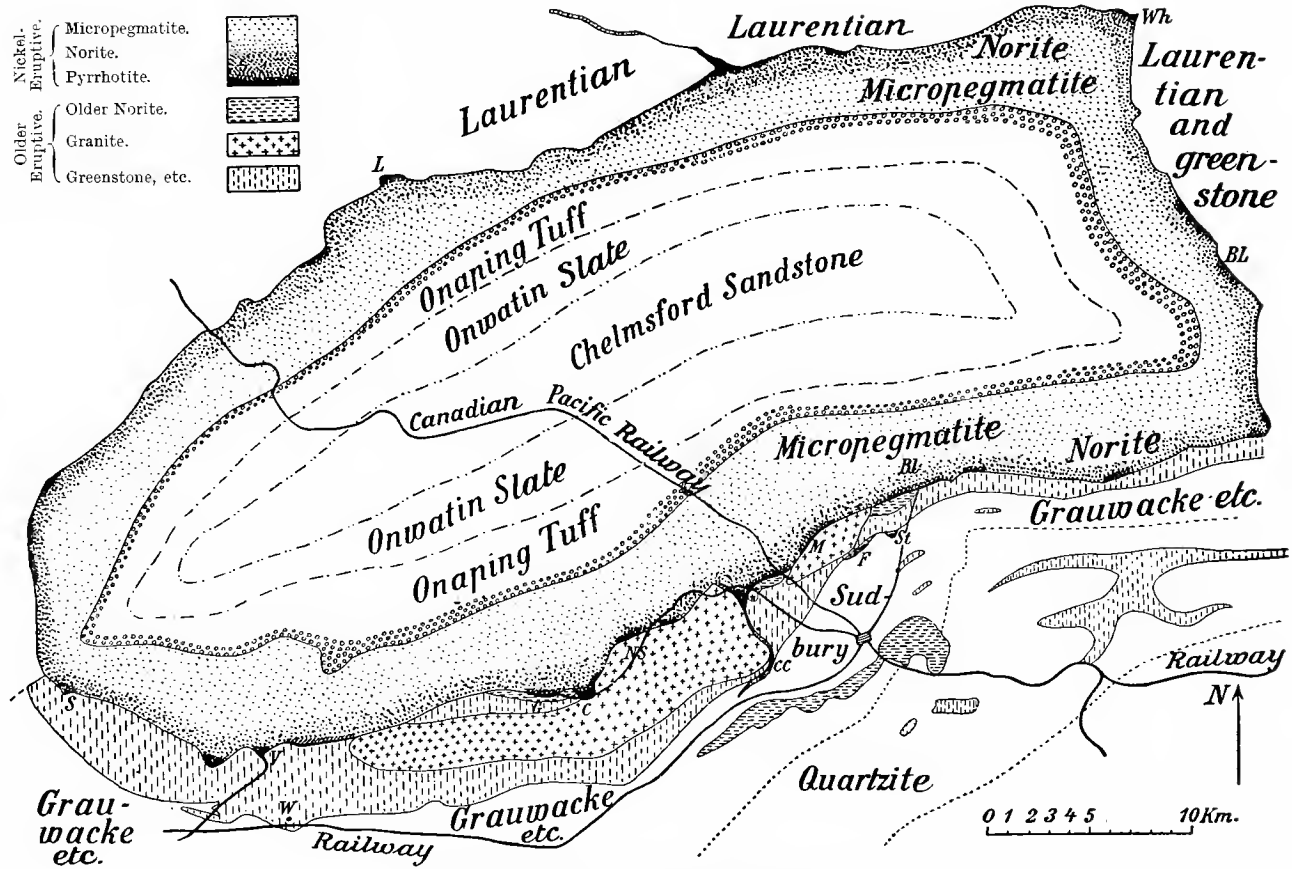

FIG. 198.—Map of the Sudbury field. Coleman, 1907.

Mines: S, Sultana; V, Victoria; W, Worthington; G, Gertrude; C, Creighton; NS, North Star; CC, Copper Cliff; M, Murray; F, Frood; St, Stobie; Bl, Blezard; BL, Blue Lake; Wh, Whistle; L, Leyack.

contents of this basin consist of conglomerate, tuff, clay-slate, and sandstone, belonging to the Upper Huronian that is to the youngest member of the fundamental crystalline schists. These rocks lie upon steeply inclined Huronian beds and Laurentian gneiss, with some eruptive rocks of nearly the same age, the complete sequence being illustrated in Fig. 199.

This eruptive occurrence, which is regarded by Canadian geologists as a gigantic laccolith younger than the sediments now upon it, varies in width around the basin between 1·5 and 8 km. Towards the outside, that is in the direction of the foot-wall, it consists of norite, chiefly quartz-norite, with about 55 per cent of silica; but towards the centre, that is in the direction of the hanging-wall, it passes gradually into a granitic rock, micropegmatite, with 67 per cent of silica.

The mines with few exceptions are found on the foot-wall limit of the eruptive syncline, that is at the contact of the quartz-norite with the old gneiss and other rocks, the deposits being particularly developed

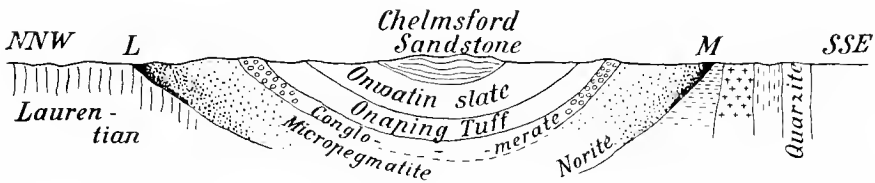

FIG. 199.—Diagrammatic section of the Sudbury field. Coleman, 1907.
L, the Levack mine; M, the Murray mine.

where the eruptive rock bays into this foot-wall. On the south side of the basin the mines Sultana, Gertrude, Creighton, North Star, Tam o' Shanter, Lady Violet, Elsie, Murray, Cameron, Little Stobie, Mount Blezard, Beatrice, Kirkwood, and Cryderman, are found. Along spurs proceeding south from the norite mass, such spurs in part resembling dykes, the following additional mines are working, Victoria, Clarabella, Lady Macdonald; while the Worthington, Copper Cliff, Evans, Frood, and Stobie mines, are situated upon smaller masses of norite in the near neighbourhood. On the north side of the basin there are but few mines working. All the deposits without exception occur in the marginal portions of the norite or quartz-norite, this rock being generally finer-grained and more basic in the immediate neighbourhood of the ore than further inside the basin.[1] Plan and section of the occurrence in the Murray mine are given in Fig. 200.

The deposits in general are stumpy in shape with the older gneiss as foot-wall; towards the hanging-wall the amount of sulphide gradually diminishes. From this feature Coleman drew the conclusion that the

[1] Barlow, 1904, p. 126.

sulphide by gravity sank to the contact below, an idea which years ago was advanced in connection with the Meinkjär mine in Norway, illustrated in Figs. 197 and 201.

Apart from a few smaller attempts mining began in this district in the year 1885. In 1886 the Canadian Copper Co., originally with a capital of two million dollars, was formed to take over and work the Copper Cliff, the Stobie, and the Evans mines. Since then the industry thus commenced has so developed till of 14,100 tons, the world's production of nickel in 1908, Sudbury delivered 8670 tons or more

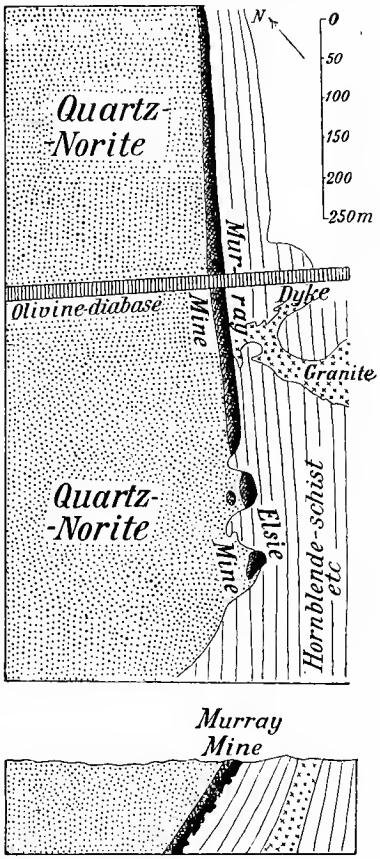

FIG. 200.—Plan of the Murray and Elsie mines, and section through the Murray mine. The nickel ore is represented black. Barlow, 1904.

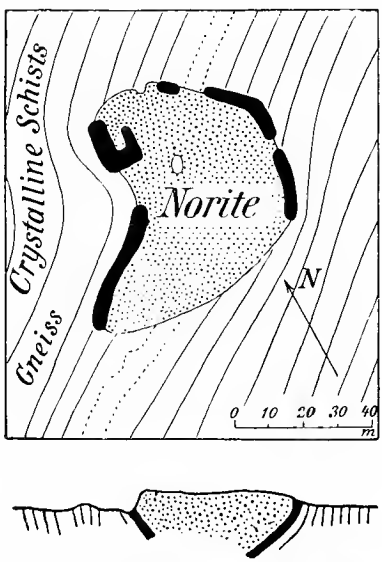

FIG. 201.—Plan and section of the Meinkjär deposit. The black areas indicate the open workings and therefore the ore. Vogt, *Zeit. f. prakt. Geol.*, 1893, Plate IV.

than one-half, the remainder coming chiefly from the garnierite mines of New Caledonia. Of late years at Sudbury approximately one-third of a million tons of ore are broken and smelted yearly, while up to and including the year 1908 roughly three million tons of ore had been produced. In this total, according to the statistics of the Geological Survey of Canada, the principal mines participated as follows:

Stobie	From 1886 to suspension of work in November 1901 and to a depth of only 80 m.	380,000 tons.
Copper Cliff	From 1886 to June 1904 and to a depth of 325 m.	330,000 „
Creighton	From June 1901–1908 and to a depth of 97 m.	1,065,000 „

The last-mentioned mine which started comparatively late is now the most important in the district and regarded as the richest nickel mine so far known in the world. The Victoria and the Garson mines during the last five years have produced about 50,000 tons yearly, while in 1906 the Crean Hill mine produced approximately 80,000 tons. The total production and the average nickel and copper content of the ore smelted at Sudbury are given in the following table :

	Total Ore Hoisted.	Total Smelted.	Copper-Nickel Matte produced.	Metal Content in Matte.		Average Metal Content of the Ore.	
				Ni.	Cu.	Ni.	Cu.
	Tons.	Tons.	Tons.	Tons.	Tons.	Per cent.	Per cent.
1890	118,000	55,000	...	...	...	...	...
1895	69,000	79,000	11,400	2100	2150	2·67	2·73
1900	196,000	192,000	21,300	3200	2950	1·67	1·59
1905	258,000	232,000	15,800	8700	4100	3·68	1·79
1907	319,000	326,000	20,000	9620	6360	2·95	1·95
1908	372,000	327,000	19,020	8670	6900	2·65	2·08

The nickel and copper contained in the ore is calculated from the amounts of these metals in the matte ; the loss in roasting and smelting therefore is not made good in the above figures. At first low-grade blast-furnace matte was produced, later however the practice has been to produce Bessemer or rich matte.

Deposits geologically similar though somewhat poorer are found at St. Stephen in New Brunswick.[1] The best-known nickel-pyrrhotite deposit in the United States is at the Gap mine, Lancaster County, Pennsylvania, which has been described by J. F. Kemp.[2] This deposit likewise occurs at the margin of a mass of amphibolite, about 600 m. long and 150 m. wide, this rock probably representing an altered gabbro. The country-rock is mica-schist. Operations at this mine were suspended in 1893 when a depth of only 80 m. had been reached.

[1] Barlow, 1904 ; Dickson, 1906.
[2] *Trans. Am. Inst. Min. Eng.*, 1894.

Norway

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At various places in Norway about fifty occurrences of gabbro carrying nickel-pyrrhotite are known. Most of these are found in the fundamental crystalline schists, such being: Romsaas in Askim with the noted spheroidal norite, and other localities in Smaalenene; Erteli, and other mines on Ringerike; some occurrences in Sigdal; Meinkjär, Bamle-Nysten, etc., in Bamle, the former lying but a few kilometres from the apatite mine of Oedegaarden; some occurrences in the neighbourhood of Tvedestrand and Arendal; Flaad in Evje and other occurrences in Säterdalen, and Senjen in Tromsö.

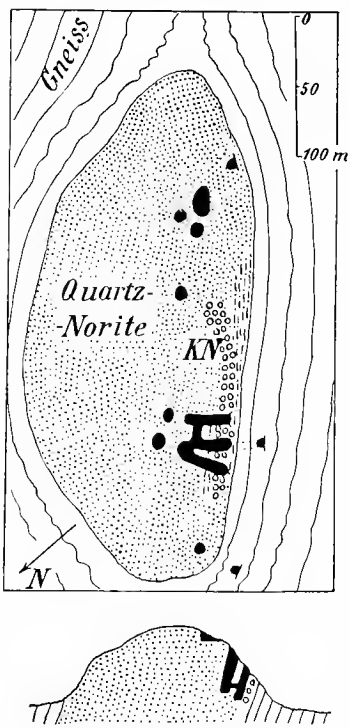

Fig. 202.—Plan and section of the Romsaas field. The black areas represent the open workings and therefore the ore. The hatched areas indicate foliated norite. Vogt, *Zeit. f. prakt. Geol.*, 1893, Plate V.

KN, spherical norite.

Other deposits are found in connection with regionally metamorphosed slates, such for instance as many old occurrences in Espedalen well inland; Nonaas and other deposits on Hosanger one of the Bergen islands; Dyrhaug and other mines at Skjäkerdalen in the Trondhjem district; Beiern and Misvärtal in Skjärstad; and Malö in Steigen.

With most of the deposits, such for instance as Erteli illustrated in Fig. 203, Meinkjär in Fig. 201, Bamle-Nysten in Fig. 142, Höiaas near Tvedestrand, Beiern, etc., the ore occurs in characteristic manner at the contact of gabbro, represented in most cases by norite, and the crystalline schists in which such gabbro is found. At Romsaas, illustrated in Fig. 202, ore is also found somewhat farther from the contact.

Microscopic investigation undertaken by Vogt upon specimens of ore from Romsaas, showed that with an increase in the proportion of sulphide, a decrease in plagioclase and an increase in hypersthene were connected. The ore occurring in streaks consists of sulphide and hypersthene with some biotite and hornblende, but contains no plagioclase. The sulphides and the ferro-magnesium silicates accordingly have increased their proportions concurrently, a fact which constitutes further evidence of the formation of these deposits by magmatic differentiation.

In the Flaad mine at Evje the ore is found within a large area of a

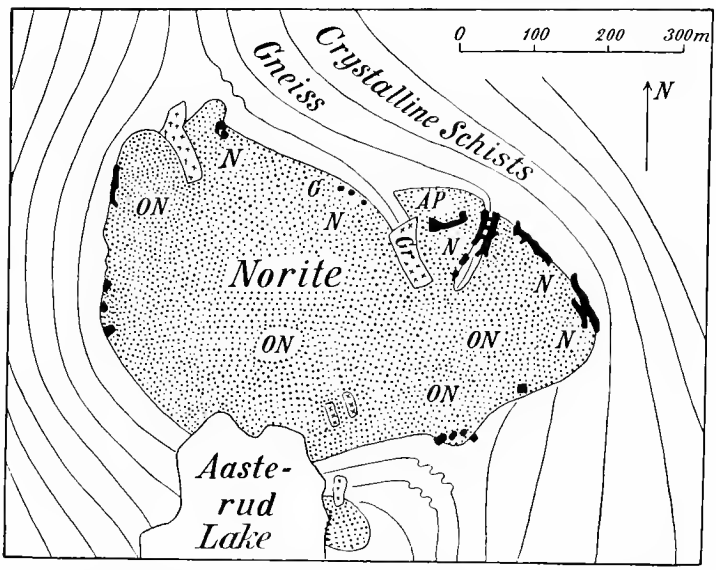

FIG. 203.—Ground plan of the Erteli field near Ringerike. The black areas indicate open workings and therefore the deposits which it is seen lie chiefly at the contact with the eruptive. Vogt, *Zeit. f. prakt. Geol.*, 1893, Plate V.

N, norite; ON, olivine-norite; G, gabbro; AP, amphibolite-picrite.

uralite-gabbro or uralite-norite poor in quartz, many square kilometres in extent. Though actually within the eruptive the ore however here also occurs near the margin. It is principally a pyrrhotite-gabbro containing 40 to 80 per cent of pyritic sulphide in addition to the ordinary gabbro minerals. It forms a series of approximately parallel though irregular streaks which, as illustrated in Figs. 204 and 205, dip at about 40° in normal uralite-gabbro. These streaks are accompanied by numerous though generally small leucokratic dykes some of which are of granite-aplite.

Many smaller norite occurrences at Ringerike, Bamle, etc., with

superficial areas between 100 and 1000 sq. m., contain small bodies of ore.

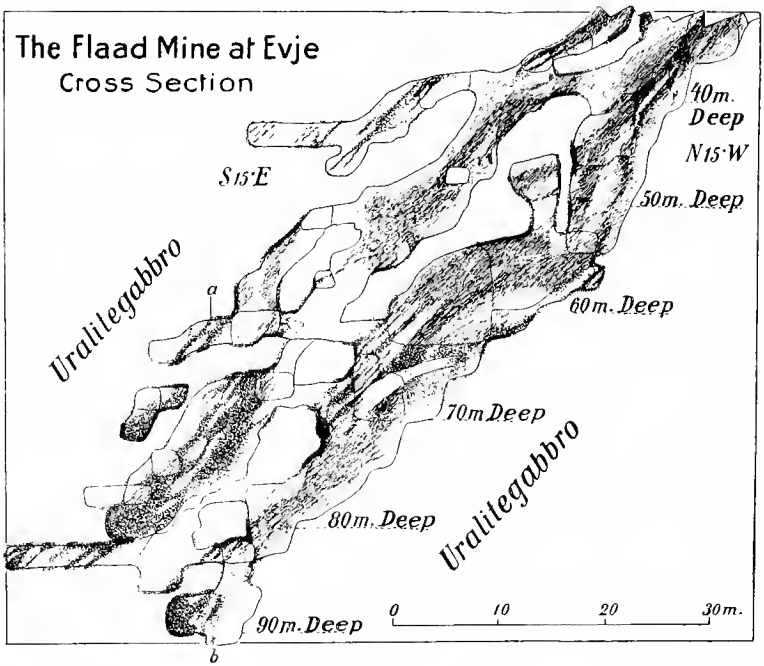

Fig. 204.

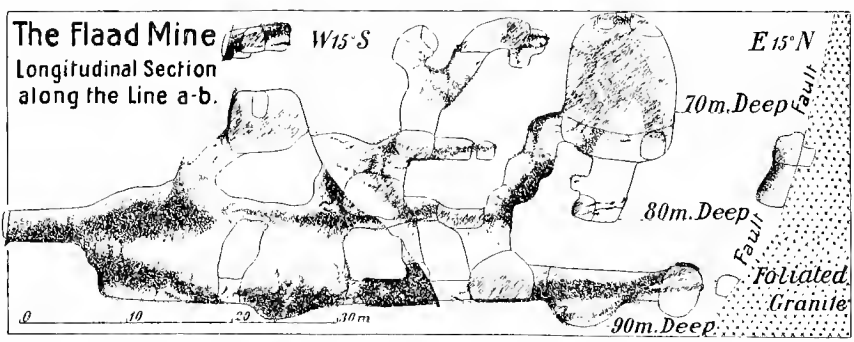

Fig. 205.

Figs. 204, 205.—Cross and longitudinal sections of the Flaad mine at Evje. The ore is indicated dark, the intensity of the darkness representing approximately the amount of ore present; the hatched portions are those which have been mined. R. Stören.

The somewhat larger occurrence of Meinkjär, illustrated in Fig. 201, with 3250 sq. m. and that of Nysten-Bamle, illustrated in Fig. 142, with 3000–

4000 sq. m., have together yielded at the most 1600 tons of ore with 20 per cent nickel, for each metre of vertical depth. Richer by far is the occurrence at Erteli illustrated in Fig. 203, which has an horizontal extent of 210,000 sq. m. This to date and to a depth of 90 m. has produced about 110,000 tons of nickel ore containing 1250 tons of nickel and 600 tons of copper.

The richest nickel mine in Norway is however the above-mentioned Flaad mine which works an ore-body occurring in a mass of uralite-gabbro about 75 sq. km. in extent. The production so far, that is between 1872 and 1908, has been about 75,000 tons of ore equivalent to 1350 tons of nickel and 800 tons of copper. The present depth is about 90 m. though the ore-body is far from exhausted to that depth.

According to calculations by Vogt[1] if the total nickel, cobalt, and copper, contained in the ore-bodies were distributed regularly over the entire eruptive masses, the results in representative cases would be :

	Nickel.	Cobalt.	Copper.
	Per cent.	Per cent.	Per cent.
Erteli	0·030	0·005	0·015
Meinkjär-Nysten . .	0·120	0·017	0·050
Beiern	0·085	0·008	0·020

Nickel mining in Norway began in the 'forties and reached its greatest importance during the period 1870–1877, the largest production in any one year having been that for 1876 when 360 tons of nickel were won. Latterly only one mine, the Flaad, continues working. In the whole of Norway roughly 400,000 tons of nickel ore have been mined and smelted. The hand-sorted ore usually yields 1·4–1·7 per cent of nickel, though exceptionally the yield may be as much as 2–2·5 per cent.

Sweden

The best-known deposit of nickel-pyrrhotite in Sweden occurs near Klefva in Småland. This was originally worked for copper and only afterwards, roughly from 1840 to 1888, for nickel. The ore occurs within a quartz-norite mass about 6 km. long and 2·5 km. wide, though these dimensions include an occurrence which is not completely connected. The quartz-norite is also associated with gabbro-diorite or uralite-norite. The ore is chiefly pyrrhotite-gabbro which occurs in five or six wide and approximately parallel streaks sharply separated from the gabbro poor in sulphide. These streaks have been disturbed by several younger faults.[2]

[1] *Zeit. f. prakt. Geol.*, 1893.

[2] B. Santesson, H. von Post, *Geol. Fören. Förh.*, 1887 ; W. C. Brögger and J. H. L. Vogt, manuscript 1887.

Other deposits occur at Ruda in Vinjåker ; in Oestergötland in the so-called diorite ; [1] at Gaddbo in Simtuva; at Ekedal in Enåker ; in Vestmanland in so-called gabbro-diorite ; and finally at Kuso and Stättberg, in Dalarne, in a gabbro-diorite and in a narrow porphyrite or diabase dyke.[2] At Lundörren between Jämtland and Herjedalen nickel-pyrrhotite occurs together with pyrite and chalcopyrite within a mass of olivine-diabase in a regional-metamorphic district. The ore is found on the foot-wall of the diabase adjacent to the enclosing slates.[3] Latterly nickel mining in Sweden has practically ceased.

Varallo, Piedmont, Italy

LITERATURE

A. W. Stelzner. Berg- und Hüttenm. Ztg., 1877, pp. 86, 87.—Badoureau. 'La Métallurgie du nickel,' Ann. des mines, Paris, 1877.—B. Lotti. I Depositi dei minerali metalliferi. Turin, 1903.—M. Priehäusser. Zeit. f. prakt. Geol., 1909, giving literature.

In the Sesia valley on the south-east slope of Monte Rosa, basic eruptive rocks occur within a zone of highly metamorphosed crystalline schists. These rocks consist chiefly of norite and gabbro together with picrite, etc. At different places, associated with highly basic segregations within the gabbro, nickel-pyrrhotite deposits are found. The Cevia mine situated 1980 m. above the sea and the Sella Bassa mine some 1700 m., were worked more especially during the nickel boom in the latter half of the past century. The yearly production then was equivalent to about 50 tons of metal.

St. Blasien in the Southern Black Forest

The mines here, now stopped for several decades, contained nickel-pyrrhotite together with some pyrite and chalcopyrite, in close association with intermediate and basic eruptive rocks very much altered. According to E. Weinschenk [4] these were originally quartz-diorite norite, gabbro proper, and probably felspathic bronzite-olivinite. These rocks in which a markedly streaked structure was developed were shattered by a granite intrusion. Weinschenk [5] regarded these nickel-pyrrhotite occurrences as secondary deposits at the contact between granite-aplite rocks and the above-mentioned intermediate and basic rocks. As already stated we cannot endorse this, but regard these occurrences also as proper magmatic segregations.

[1] G. Landström, *Geol. Fören. Förh.*, 1887.
[2] G. Löfstrand, *Geol. Fören. Förh.*, 1903.
[3] Vogt, *Schwed. geol. Unters.* Ser. C, No. 89, 1887.
[4] *Zeit. f. prakt. Geol.*, 1907. [5] *Ante*, p. 288.

Sohland and Schweidrich

LITERATURE

R. Beck. Zeit. f. prakt. Geol., 1902, 41 and 379; more exhaustively Zeit. d. D. Geol. Ges., 1903; Upon Schweidrich.—H. B. von Foullon. Jahrb. d. geol. Reichsanst. Vienna, 1892.

These two occurrences lie about 5–6 km. from one another on the Saxon-Bohemian frontier, the first being in Saxony and the latter in Bohemia. Though of the same class they differ from the nickel-pyrrhotite deposits which have just been described in so far that they are not connected with basic plutonic rocks but with the chemically equivalent volcanic rocks. The basic dyke at Sohland is not less than 700 m. long and is perhaps even 1500 m., with a breadth of 10–20 m. This by Beck has been described as a biotite-proterobas greatly altered. The ore consists chiefly of nickel-pyrrhotite with 5·5–6 per cent of nickel in the ore mined; pyrite and chalcopyrite are subordinate as is the case with all these deposits. All the ore occurs on the wall between the dyke and the enclosing granite. In its immediate neighbourhood the dyke rock exhibits remarkable basic segregations containing much spinel, sillimanite, corundum, etc., recalling the frequent tendency of the gabbro-magma in the immediate neighbourhood of the nickel-pyrrhotite deposits to show a marked differentiation.[1] The view held by Beck regarding the genesis of these deposits has already been given.[2]

The deposit at Schweidrich near Schluckenau appears also to be an impregnation, along one wall of a basic dyke, running in a N.N.W. direction in the Lausitz granite. Economically however it may be said to have no importance. The occurrence at Sohland has in the last few years been prospected and worked upon a small scale.

Niccolite and Chromite Occurrences: Los Jarales, Spain

In connection with the nickel-pyrrhotite deposits the above occurrences, found 35 km. north-west of Malaga in Spain, may fitly be described. According to F. Gillman[3] these deposits occur below water-level in serpentinized peridotite, represented by lherzolite or saxonite. Three types of ore may be differentiated: 1, the chromite type; 2, the augite type; 3, the norite type. The first consists of a fine-grained mixture of chromite with niccolite, NiAs, small grains of the former being embedded in the

[1] *Ante*, p. 281.

[2] *Ante*, p. 288.

[3] *Inst. Min. Met.*, London, 1896; reviewed by Krusch, *Zeit. f. prakt. Geol.*, 1897; and Vogt, *Ges. der Wiss.*, Christiania, Mar. 12, 1897.

latter. The second type is distinguished by the amount of augite and niccolite present; and the third by the presence of plagioclase and pyroxenes in addition to the two ores.

As suggested by Gillman, without doubt here it is a question of the concurrent magmatic segregation of both the chromite and the niccolite. Near the surface the niccolite is altered to a nickel-magnesium silicate, garnierite, or pimelite. From this fact however no general conclusions concerning the origin of garnierite deposits may in our opinion be drawn.

These deposits have little extent and have only been prospected or worked on a small scale at times during the period 1850–1894.

ANNEX

Magmatic Bornite Deposits in Cape Colony

LITERATURE

A. Schenck. Zeit. d. D. Geol. Ges., 1901, Vol. LIII., p. 64.—O. Stutzer. Zeit. f. prakt. Geol., 1907, p. 371, with review of pertinent papers by Ronaldson and Rogers.

These deposits occur at O'kiep in Klein-Namaqualand in the north-western portion of Cape Colony. The ores are chiefly bornite and chalcopyrite, with smaller amounts of chalcocite, pyrrhotite, molybdenite, etc. They occur scattered partly as small particles and partly as larger masses up to several metres in diameter, in basic eruptive rocks which formerly were repeatedly described as diorite. The constituents of this rock are hypersthene, magnetite, bornite, a little biotite, and some basic plagioclase. The bornite is just as much a constituent of this rock as are the hypersthene and the magnetite.

The view put forward by Schenck in 1901 and again expressed by Stutzer in 1907 that these deposits are true magmatic segregations appears to us to be justified although, with bornite present, great care must be taken in coming to a conclusion since that ore usually belongs to the cementation zone.

These deposits are very important. They have been in continuous operation since the commencement of the 'fifties. Of late 5000–7000 tons of copper have been won annually from them, though whether to these figures of production deposits of other genesis contribute can not be said.

The Monte Catini District

In the Monte Catini district and at many other places in Tuscany rich sulphide copper ores, such as bornite, chalcopyrite, chalcocite, with

pyrite and some galena, occur within comparatively small masses of basic eruptive rock of Tertiary age. These have generally been spoken of as serpentine or as ophiolitic rocks, while in detail serpentine, diabase, and euphotide, the variety of gabbro, have been distinguished.

Two eruptions may be recognized, an older now represented by lherzolite, and a younger from which olivine-gabbro and olivine-diabase resulted. With these the ore is most certainly connected since no mass of eruptive rock, however small, exists which does not contain at least a small amount of ore, generally in association with olivine-gabbro.

B. Lotti in a number of papers [1] has defended the view which he put forward that these occurrences were the result of magmatic differentiation. This interpretation however seems questionable since the rocks in which the ores occur are greatly decomposed and the ores themselves, including the great lumps of native copper occasionally found, bear all the signs of cementation. It would appear rather to be a case of subsequent concentration of ore material originally finely distributed and of which the genesis has not yet been solved. This alternative view is supported by the consideration that in the decomposition of the rock the same agencies were at work which are so effective in the cementation zone of copper deposits. In this connection reference is made to the formation of bornite from ordinary chalcopyrite as illustrated in Fig. 99.

(2) The Intrusive Pyritic Sulphide Deposits

A number of important deposits wherein relatively large and compact masses of different pyritic sulphides such as pyrite, phyrrhotite, and some chalcopyrite occur concentrated, are often considered together as one group, though geologically and also mineralogically they often differ materially. As the result of recent investigation some of these deposits, Rammelsberg for instance, are now with certainty recognized as sedimentary; those of Meggen and Schwelm are decidedly of metasomatic character; those of Traversella and Brosso in Piedmont, are of contact-metamorphic origin; while finally others, and these the most important, are according to our view to be regarded as the products of magmatic differentiation.

As long as the unity of this 'pyritic sulphide' group or more shortly 'pyrite' group was assumed, great controversy centred around the question of its genesis. Krusch [2] however pointed out that the maintenance of a simple pyrite group in any natural classification of deposits gave to pyrite such a preference as no other mineral enjoyed, since by doing so the substance of the deposit would become the ruling principle in the classifi-

[1] *Zeit. f. prakt. Geol.*, 1894, p. 18. 'I Depositi dei minerali metalliferi.' Turin, 1903.
[2] *Untersuchung und Bewertung der Erzlagerstatten.*

cation and not the far more important genesis. Clearness concerning genesis and the advance in its acknowledgment demand that the old pyrite group be dissolved and that the individual deposits, hitherto classed together, be distributed among those different natural groups to which by their genesis they belong. Here therefore only those assumed to be the products of magmatic differentiation are treated, to which class we consider the occurrences in Norway, those of the Rio Tinto district in southern Spain, and in addition that of Bodenmais, belong. It is fairly certain also that the pyrite occurrence of Sain Bel near St. Etienne in France, the pyrite masses of Agordo and Gavorrano in Italy, and perhaps also the deposit of Schmöllnitz in the Carpathians, belong to this class.

It is characteristic of all of these that they occur in areas of regional metamorphism. Generally they are conformable with the enclosing slates; often the pyrite appears slab-like or even occurs in beds alternating with the country-rock, while at times the slates are traversed by pyrite. The deposits not infrequently occur along zones of disturbance or other tectonic planes, while a breccia structure has repeatedly been observed in places, pyrite being the cementing material. In certain districts they occur regularly and in close connection with eruptive rocks, especially with basic rocks but more seldom with such as are intermediate. In isolated cases the pyrite bodies are observed to have been traversed by later intrusions of the same eruption.

The most important ore is pyrite, not marcasite, accompanied in places by pyrrhotite by which also it is sometimes replaced. The copper content arising from the admixed chalcopyrite is usually 0·5–3·5 per cent, higher than which it seldom goes. In but few cases is the pyrite free from copper. Sphalerite and galena usually occur quite subordinately. The manganese content is very low throughout being generally under 0·1 per cent; the nickel-cobalt content similarly reaches only 0·05–0·15 per cent. In many places some arsenic is present, though antimony and bismuth are seldom met. A small silver content, generally 25–50 grm. per ton, is fairly constant, while the amount of gold present is generally one-twenty-fifth to one-hundredth that of the silver.[1] In isolated cases as for instance at Fahlun, the gold content is materially higher. Titanic acid practically speaking is absent. The phosphorus present is also so small in amount that in the residues after treatment only 0·008–0·01 per cent is found.

The ore occurs mixed chiefly with quartz, hornblende, and magnesia-mica, and to a less extent with garnet, augite, epidote, zoisite, disthene, tourmaline, etc. Fluorite and the carbonates are of small importance, while barite as a primary mineral appears to be absent.

From the conformity of the deposits with the slates, the slab-like

[1] *Ante*, pp. 163 and 165.

structure of the pyrite, and the alternation of pyrite with country-rock, many authorities conclude that the deposits are sedimentary. However from the unconformity observable in more places than one, from the occurrence of breccia in certain districts, and from the not-infrequent occurrence of the pyrite along planes of movement and zones of disturbance not only in the slate but also in eruptive rock, the epigenetic nature of the pyrite is established. The regular connection of the pyrite beds with eruptive rocks in certain districts and their rupture by later intrusions from the eruption are further evidences that the formation of the pyrite rests upon eruptive phenomena. From analogy with the nickel-pyrrhotite deposits and from the manner in which the ore and gangue are crystallized it would also follow that the deposits have arisen from a magma at its consolidation. Further discussion of this question of the genesis of these pyrite deposits is given later when describing the deposits in Norway.

Economically speaking several of the deposits here to be described are of the greatest importance. Formerly these were worked exclusively for copper but from about 1860 they have also been worked for the pyrite itself, this usually containing 45–49 per cent of sulphur. Pyrite is used for the production of sulphur and of late years also for that of sulphuric acid. Corresponding to the greatly increased demand for pyrite for these purposes in recent years the production from the principal mines, as indicated in the following table, has risen enormously:

In Metric Tons.	1870.	1880.	1890.	1900.	1907.
Produced—					
Southern Spain . .	about 400,000	1,480,000	2,320,000	2,840,000	3,200,000
,, Portugal . .	150,000	300,000	300,000	403,000	351,000
Exported—					some
Southern Spain . .	250,000	520,000	850,000	950,000	1,500,000
,, Portugal . .	100,000	180,000	115,000	(some	250,000 ?)
Produced—					
France, chiefly Sain Bel .	66,400	92,800	208,200	304,000	280,000
Norway	80,000	75,000	60,000	100,000	235,000
Schmöllnitz, Hungary .	...	...	38,000	77,000	80,000
					some
Italy	...	5,000	15,000	70,000	80,000

In the above table the latest export figures for Portugal not being at the time available are not included. Outside of Sain Bel the pyrite production of France latterly has only amounted to some thousands of tons per year. The production in Italy has of late years come not only from Gavorrano and Agordo but also from Brosso, Traversella, and perhaps also from other mines.

The finest pyrite deposits in the world are those of the Rio Tinto or Huelva district including those occurring within the adjoining Portuguese

territory, which altogether and up to the end of the year 1908 had produced some 125 million tons. Next in Europe comes that of Sain Bel in France which from 1872 to 1908 produced some 7·5 million tons.

Norway

LITERATURE

Th. Kjerulf. Die Geologie des südlichen Norwegens. Bonn, 1880; Nyt. Mag. f. Naturv. XXVII., 1883; XIX., 1885.—A. Helland. Kiese in gewissen Schiefern in Norwegen, Universitätsprogramm. Christiania, 1873.—H. Reusch. Nyt. Mag. f. Naturv. XIX., 1885.—J. H. L. Vogt. 'Salten und Ranen,' Norw. Geol. Unters. No. 3, 1890, 1891; 'Über die Kieslagerstätten vom Typus Röros und Rammelsberg,' Zeit. f. prakt. Geol., 1894; 'Problems in the Geology of Ore-Deposits,' Trans. Am. Inst. Min. Eng. XXXI., 1902; Die Erzlagerstätten und der Bergbau im nördlichen Norwegen. Christiania, 1902; Über Nickel. Christiania, 1902; Der Bergbau in dem Trondhjemgebiet. Trondhjem, 1905; the articles before mentioned on p. 246 in the Norw. Geol. Unters. Jahrb., 1905. —W. C. Brögger. Vortrag, Ges. d. Wiss. Christiania, Sept. 1901; Reviews of articles by Vogt and Brögger in the Geol. Centralbl., III., VI., VIII.; Zeit. f. prakt. Geol., 1899, 1900, 1904, 1906.—A. W. Stelzner. Die Sulitjelmagruben. Freiberg, 1891.—Hj. Sjögren. 'Über Sulitjelma,' Geol. Fören. Förh., 1894, 1895, 1896, 1900.—O. Nordenskjöld. 'Über Bossmo,' ibid., 1895.—O. Stutzer. Österr. Zeit. f. Berg- u. Hüttenw. 1906, No. 44; Zeit. f. prakt. Geol., 1909, No. 3.—Glinz. Berg- und Hüttenm. Zeit., 1902. —Everding. Ibid., 1903.

The Norwegian pyrite deposits are widely distributed over that country. To the north they are found at Birtavarre, Sulitjelma, Bossmo, etc.; in the centre at Ytterö, Meraker, Meldalen, Killingdal, Kjöli, Röros, Röstvangan, Foldal, etc., in the Trondhjem district; and towards the south in Söndhordland and Vigsnäs. All occur at various horizons within Cambro-Silurian formations and always in areas of regional metamorphism; in the fundamental crystalline schists on the other hand they are entirely absent. The Palæozoic formations in which they occur are traversed by a large number of eruptive rocks which form a complete series extending from sodium-granite on the one side to gabbro or even to peridotite on the other. These are often more or less altered, the gabbro indeed is rarely unaltered but occurs chiefly as saussurite-gabbro or even as zoisite-amphibole schist. By observation of the petrographical gradations and by analyses it can be shown that this schist with 46–50 per cent of SiO_2 has resulted from the gabbro by pressure metamorphism. Nevertheless the rocks in all cases are plutonic, occurring often as illustrated in Figs. 207, 211, and 212, in the form of laccoliths, of which in more than one case both the upper and lower surfaces can be seen. The intrusion of these eruptive rocks probably took place concurrently with the folding of the beds, so pronounced in this hilly country. In addition to these plutonic occurrences, volcanic sheets are perhaps to be found in the district of Trondhjem.

The pyrite deposits only occur within those Palæozoic areas which

are crossed by eruptive rocks and then generally only in close proximity to or even within gabbro. This phenomenon was noted forty years back by Th. Kjerulf, since when it has been corroborated by later investigation, especially by Vogt. Of twenty-eight more important occurrences reviewed by this authority in 1894, twenty-six were at that time shown to be in the immediate neighbourhood of saussurite-gabbro, and in the case of the remaining two the presence of basic eruptive rock in their neighbourhood was also established later.[1] Of late years, and more particularly in Northern Norway, a large number of new pyrite deposits have been found,

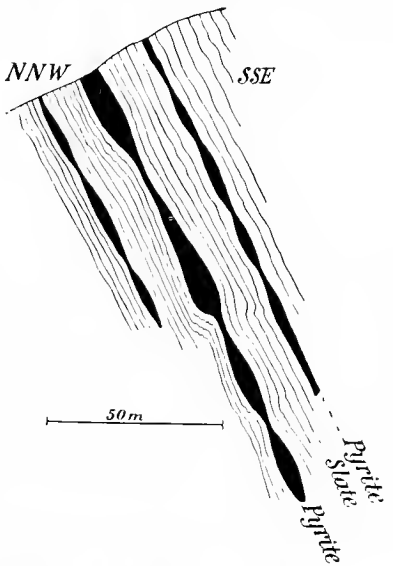

Fig. 206.—Section of the Varaldsø mine showing three pyrite deposits lying conformable to one another and close together. Vogt. *Zeit. f. prakt. Geol.*, 1893.

all in the neighbourhood of basic rock more or less strongly foliated. For the greater part these are conformable to the schists in which they are embedded and are generally found within less than one hundred metres of a gabbro mass. An excellent example of such a geological position is afforded by the Mug mine near Röros, illustrated in Fig. 207, where the distance between the pyrite deposits and the saussurite-gabbro above them hardly reaches 50 m. With some deposits the distance between pyrite and gabbro is somewhat greater and at low angles of dip the horizontal distance may measure as much as one kilometre. More rarely the deposit does not lie in the schists but within the mass of gabbro itself, and then generally along some plane of movement or crush as illustrated in Fig. 208.

[1] Vogt, *Zeit. f. prakt. Geol.*, 1894, p. 124.

These deposits according to the mineral predominantly contained may be divided into several classes, all of which however are connected by a full number of intermediate grades. These are as follows :

1. Occurrences consisting chiefly of pyrite, usually with some chalcopyrite and sphalerite, but generally without pyrrhotite, and with only traces of galena. The hand-picked ore of this class, or that obtained by concentration, contains as a rule about 44–46 per cent of sulphur with 1·7–3·5 per cent of copper.

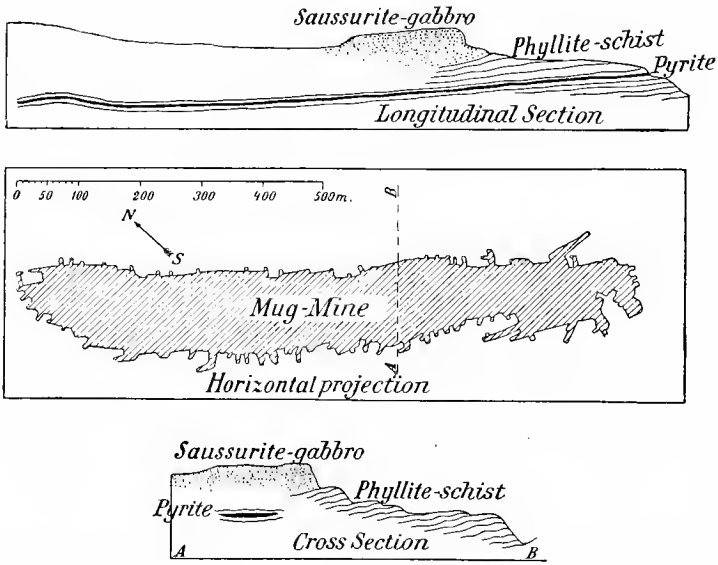

Fig. 207.—Horizontal section through the Mug mine with longitudinal and cross sections. Vogt, *Zeit. f. prakt. Geol.*, 1894.

2. Occurrences of pyrite and chalcopyrite with comparatively much quartz, hornblende, etc.

3. Occurrences of pyrrhotite with chalcopyrite, quartz, etc.

The smelting ore of these two latter classes contains generally 4–6 per cent of copper and 0·1–0·2 per cent of nickel and cobalt.

Arsenic is either completely absent or its amount hardly reaches 0·1 per cent. Galena is poorly represented though it occurs here and there as do also tetrahedrite and bornite. The small though constant presence of gold and silver has already been mentioned on pp. 163 and 165. Magnetite is absent from most occurrences though in isolated cases and to a limited extent it may even be the principal mineral. The Fosdalen mine at

Trondhjemsfjord for instance is working an ore-body which consists of 70 per cent of magnetite, 6 per cent of sulphur, traces of chalcopyrite, and about 24 per cent of quartz, hornblende, etc.

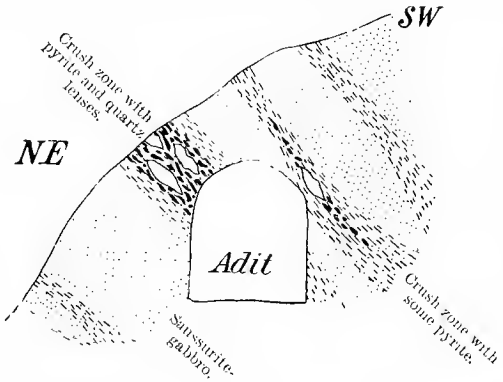

FIG. 208.—Section in the Storhusmand mine in Meraker. Vogt, *Zeit. f. prakt. Geol.*, 1894.

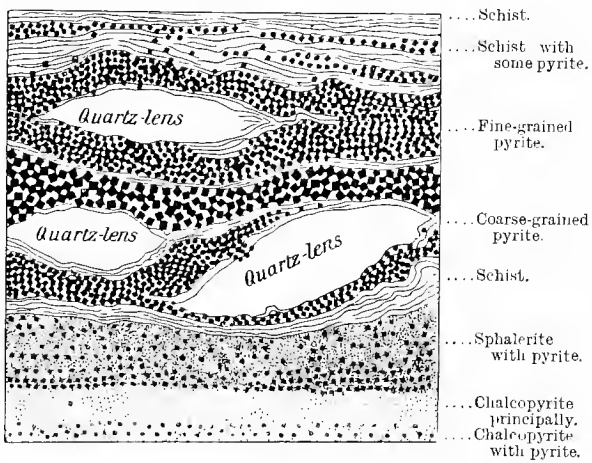

FIG. 209.—Specimen from the Kongens mine near Röros ; one-half natural size. Vogt, *Zeit. f. prakt. Geol.*, 1894.

The view expressed by Klockmann [1] that the pyrite, FeS_2, of the Norwegian deposits has often been altered by contact-metamorphism to pyrrhotite, FeS, appears to lack proper foundation. In the now-abandoned Vigsnäs mine, which between the years 1865 and 1894 produced about 900,000 tons of pyrite from deposits dipping at a high angle, the average copper content of the pyrite sank from about 3 per cent in the upper levels

[1] *Zeit. f. prakt. Geol.*, 1904, p. 153.

to about 1 per cent at a depth of 700 m. No similar decrease in content has however been observed in the other Norwegian occurrences, most of which lie fairly flat, nor on the other hand has any secondary enrichment similar to that found in the Huelva district been observed.

With all these occurrences the most important gangue minerals are quartz, hornblende, biotite, chlorite, talc, and exceptionally garnet. In addition to these the following have been observed to occur: pyroxene, epidote, zoisite, and various carbonates, together with disthene, titanite, fluorite, and tourmaline, as rarities. Of secondary formation are various zeolites, as well as the anhydrite occurring at Sulitjelma. Fragments and flakes of slate often occur within the ore, and the deposit on its flanks often passes over into zones impregnated with pyrite and resembling fahlbands.

The ore has as a rule a banded structure which arises from the varying composition of the individual layers. This structure which is illustrated in Fig. 209, is often strengthened by the frequent inclusion of slate and quartz lenses. It is also very characteristic of these deposits that while they often possess considerable extension in a direction approximately that of the dip, they have a relatively small extension along the strike and very moderate thickness. Their form has often been described as resembling that of a flat rule or of a cigar pressed flat, a description which according to Fig. 207 appears not inappropriate. Dimensions of some of the principal deposits are given in the following table:

District.	Name of Mine.	Length opened to date generally along the dip.	Width at right angles to length.	Average width.	Dip of surrounding Slates.
		m.	m.	m.	
Röros	Kongens	2000	50–150	1·0– 5·0	Variable
	Storvarts	1400	120–300	0·5– 3·0	6°
	Mug	1250	110–160	0·2– 1·5	4°
Sulitjelma	Giken	900	150–180	0·5– 2·5	25°–30°
	Charlotte	600	250–300	0·3– 2·0	20°–25°
	Ny-Sulitjelma	650	200–250	2·0– 9·0	33°–45°
Lillefjeld	Meraker	500	100–120	1·0– 3·0	60°
Killingdal	...	500	65–85	2·0–10·0	25°

At Killingdal and at Sulitjelma where the mines have only been working during the last decades, the true length of the ore-body will undoubtedly ultimately be proved to be greater than that at present exposed. The dip of the country-rock is generally fairly flat, being often between 5° and 35°, while the angle between the direction of this dip and the extension of the pyrite bodies is often from 10–30°, though sometimes it is greater. In cases of such divergence it is said that the mines 'pitch into the country.' In many cases also it has been established that the extension of the pyrite

body is parallel to the direction of folding as indicated in Fig. 210, or to the extension of the surrounding slates.

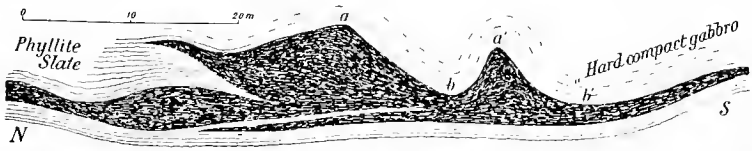

Fig. 210.—Cross section of the pyrite body at Killingdal. The length of this body runs with the anticlinal and synclinal axes represented by the points *a*, *a* ; *b*, *b*, respectively. Vogt.

In numerous cases the deposits occur near the foot-wall of the gabbro between a hard compact rock, locally termed *Haardart*, and fissile slates.

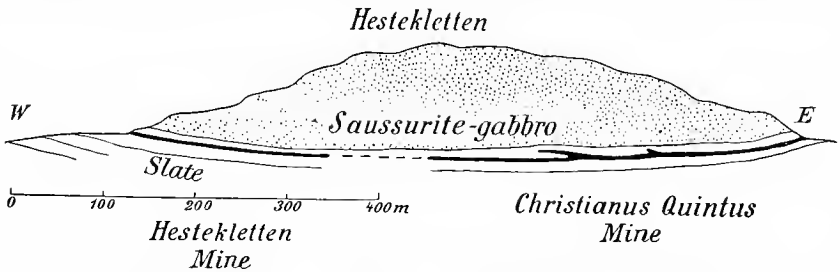

Fig. 211.—Section of the Quintus-Hestekletten mine at Röros. A section along a north-south line would present the same picture. Vogt.

Only quite exceptionally do they occur near the hanging-wall. Often, as illustrated in Fig. 207, the occurrence may be found some 50 m. below the contact. The deposit in the Quintus-Hestekletten mine at Röros,

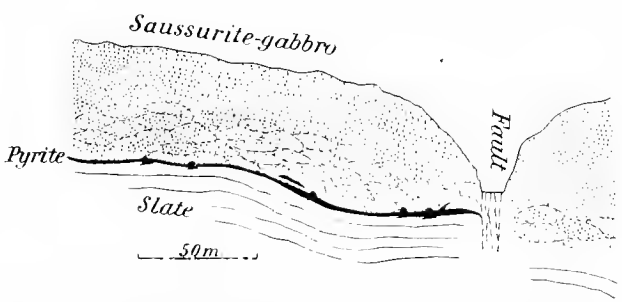

Fig. 212.—Section parallel to the outcrop at the Moskedal mine, Reisen. Vogt.

illustrated in Fig. 211, and that of the Moskedal mine in the district of Tromsö, illustrated in Fig. 212, both occur actually at the lower contact of an occurrence of gabbro.

At Sulitjelma a pyrite zone about 8 km. long is found on the north

side of the Langvand between fissile mica-schist below, lying fairly flat, and a series of relatively compact rocks above. These compact rocks are chiefly zoisite-amphibole schists which originally were probably foliated gabbro. Within this zone, which generally speaking is but a valueless impregnation resembling the fahlbands, there occur at least six valuable pyrite bodies, the dimensions of which may be gathered from the table given above.

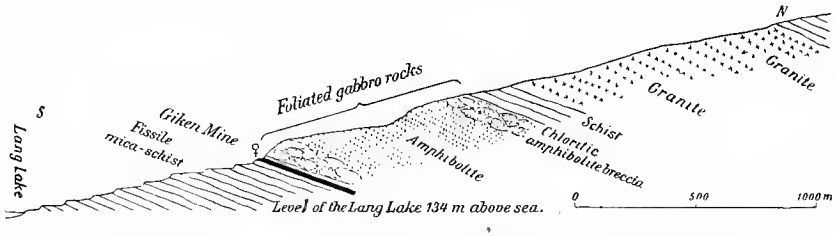

FIG. 213.—Section through the Sulitjelma field in the neighbourhood of the Giken mine on the north side of the Lang Lake.

A similar pyrite zone with occasional bodies of ore is also found on the south side of the Langvand.

Even where the slate of the country-rock is regular in strike and dip, as for instance at the Mug mine illustrated in Fig. 207, many folds and bends may nevertheless occur within the ore-body itself, as illustrated in Fig. 214. Particularly in the hanging-wall of a deposit the pyrite often

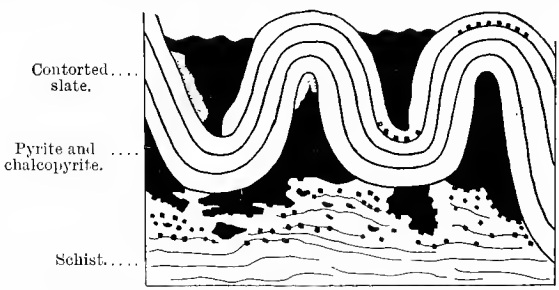

FIG. 214.—Specimen from the Kongens mine near Röros; the stippled areas are of quartz; one-half natural size. Vogt, *Zeit. f. prakt. Geol.*, 1894.

sends off branches and veins which enclose rock fragments, while occasionally occurrences of breccia may be observed in close connection with the deposit.

The pyrite body at the Mug mine consists chiefly of pyrrhotite and chalcopyrite with some quartz, together with innumerable fragments of country-rock which evidently have resulted from a sliding and grinding movement along one special bed. The Lökken mine at Meldalen exploits

in greater part a veined zone one hundred metres wide, the structure of which is illustrated in Fig. 215.

With regard to the genesis of these deposits, a sedimentary origin was argued in the 'seventies, more particularly by Helland who in the 'eighties was supported by Vogt and in 1891 by Stelzner. The frequent branching of the ore-bodies, the breccia structure just described occurring both on a small and on a large scale, and the occurrence of the deposits along planes of movement within eruptive areas, point nevertheless with certainty to an epigenetic origin. Some authorities have advocated an origin by hydrothermal and metasomatic processes, but such views find no support in the observed facts. From their intimate association with gabbro or foliated gabbro Kjerulf long ago drew the conclusion that the ore-bodies must

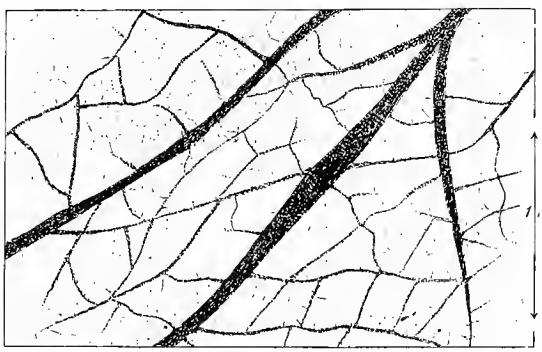

FIG. 215.—Pyrite breccia from the Lökken mine, the pyrite being represented black. Smaller veins are seen to branch from the larger ones.

stand in some sort of genetic relation to gabbro, a view confirmed by later investigation, especially that undertaken by Vogt. The pyrite bodies are in places, as for instance in the Lökken and Höidal mines at Meldalen, traversed by dykes of diabase or of granite which represent the later effusions of the eruption. The formation of these pyrite bodies is therefore contemporaneous with the magmatic period of the eruptive rocks. It follows from the form and structure of the deposits that they could not have been formed by long-continued deposition from different solutions, but that the whole of the material must have been introduced or injected at once. From these considerations alone it may be concluded that these pyrite deposits are the products of magmatic differentiation.

Again, as Brögger remarked, the idiomorphic and resorbed crystals of pyrite found, indicate that these deposits must have been formed by consolidation from a magmatic solution. The cubes of pyrite, sometimes as large as the fist, which were the first products of crystallization from

the magma, correspond structurally and genetically for instance with the quartz dihexahedra of quartz-porphyry. Attention is here directed to the statements of E. Weinschenk concerning the crystallization and subsequent resorption of different minerals found within the pyrite deposit of Bodenmais, more fully mentioned on p. 339.

These deposits, containing as they do but 0·1–0·2 per cent of nickel and cobalt, differ mineralogically and chemically no less than they do in relation to their shape, from the nickel-pyrrhotite deposits, though these also are associated with gabbro. There are however gradations between the two classes. For instance a deposit of pyrrhotite and chalcopyrite with some pyrite at Fäö in the neighbourhood of Vigsnäs, must be regarded mineralogically, structurally, and morphologically, as an ordinary pyritic ore-body. Since however it contains about 2·5 per cent of nickel and cobalt chemically it is closely connected with the nickel-pyrrhotite deposits; Vogt indeed quoted this connection as further evidence that these pyrite deposits like the nickel-pyrrhotite deposits were magmatic segregations.

In some districts, as for instance in the schist country of Värdalen in the district of Trondhjem, the two classes of sulphide deposits occur together, those of nickel-pyrrhotite within the gabbro or immediately at its margins, and the pyrite occurrences in the neighbouring schists. It follows therefore that those physical-chemical processes upon which the original separation of the two classes of deposit rests cannot be identical in all their relations. Among other features it is common with both classes that the pyrite crystallize first. In addition, with each it is found that the ore rich in copper occurs more often in the marginal portions of the deposit, a disposition which may be explained by magmatic differentiation *in situ*, that is within the already separated sulphide magma.

Where the nickel-pyrrhotite deposits occur at the contact of gabbro and schist they occasionally send spurs of fahlband character into the surrounding schistose gneiss, this, as mentioned on p. 285, being repeatedly the case at Ringerike. These fahlbands of nickel-pyrrhotite, which are seldom more than 20 m. in length, show a striking structural similarity to the impregnations which accompany the pyrite deposits. As with the chromite- and the nickel-pyrrhotite deposits so also is it the case with the pyrite deposits that the important occurrences as those of Sulitjelma, Meldalen, Röros, Foldal, Vigsnäs, etc., all occur in districts where eruptive rocks are strongly represented. The gabbro which accompanies them is a plutonic or deep-seated rock generally introduced in the form of laccoliths and doubtless under very high pressure. The same dynamic conditions also controlled the injection of the sulphide fractional magmas separated from the original gabbro magma, while at the same time they

explain the curious shape of these deposits. Generally no special fissures were formed for the injection but the pyrite magma was forced along the bedding- and fracture-planes already existing. The conformity between deposit and schists, usually to be observed, and the occurrence of the former along planes of movement in the gabbro, are thus explained. In addition, an explanation is afforded of the frequency of the deposits immediately at the contact of a compact rock above and a fissile schist beneath, as illustrated in Figs. 210, 211, and 212. With the forced entry of the sulphide magma, movement and trituration took place, often, as illustrated in Fig. 214, accompanied by contortion, or by the formation of breccia such as that illustrated in Fig. 215. The strange drawn-out form and the frequently observed parallelism of the deposit to the folds and strike of the schists are also to be explained by intrusion under dynamo-metamorphic pressure.

From the foregoing it will be seen that the pyrite deposits may be regarded as laccoliths on a small scale. Since the sulphide magmas were very fluid they were able to find their way along the foliation planes of the schistose country-rock, to form there impregnation zones resembling fahlbands. The occurrence of such impregnated zones along the continuation of the pyrite bed proper is thus explained.

Following Brögger and Vogt, the origin of the Norwegian deposits by magmatic intrusion has lately—in 1906 and 1909—also been advocated by O. Stutzer.

This view is also supported by the fact that the minerals accompanying the pyrite, namely quartz, hornblende, etc., are especially prone to be formed under conditions of dynamo-metamorphism.

As far back as the first half of the seventeenth century a number of copper mines were working these deposits in the Trondhjem district. At Röros work began as early as the year 1644 since when it has continued uninterrupted to this day. At Sulitjelma in Nordland, at present the most important mine, work was first begun towards the end of the 'eighties. Altogether about 125,000 tons of copper have hitherto been produced from the pyrite deposits of Norway, in addition to which since the 'sixties about four million tons of pyrite have been obtained. This pyrite contains generally 44–46 per cent of sulphur and some copper; arsenic is generally absent or present to the extent of less than 0·01 per cent. The rate of output of pyrite has of late risen from 60,000 to 80,000 tons per year, as it was from the 'sixties to the 'eighties, to present figures of about 250,000 tons, in addition to a metallic copper production of about 1500 tons. Approximately one-half of these present figures are contributed by Sulitjelma alone, a proportion which will increase when the projected enlargement of the work at that place is complete.

Fahlun—Sweden

The famous old deposit at this place according to A. E. Törnebohm [1] lies in grey quartzite with granulitic gneiss. In the vicinity eruptive rocks such as granite and diorite, together with dykes of felsite and trap, are found, these dykes crossing the ore-deposits. These deposits occur within a superficies about 600 m. long and 400 m. wide as irregular masses enclosed to a great extent by crushed country-rock. Three types of ore are distinguished :

I. Soft ore, consisting chiefly of pyrite, some chalcopyrite, quartz, hornblende, etc. This class corresponds to the Norwegian pyrite.

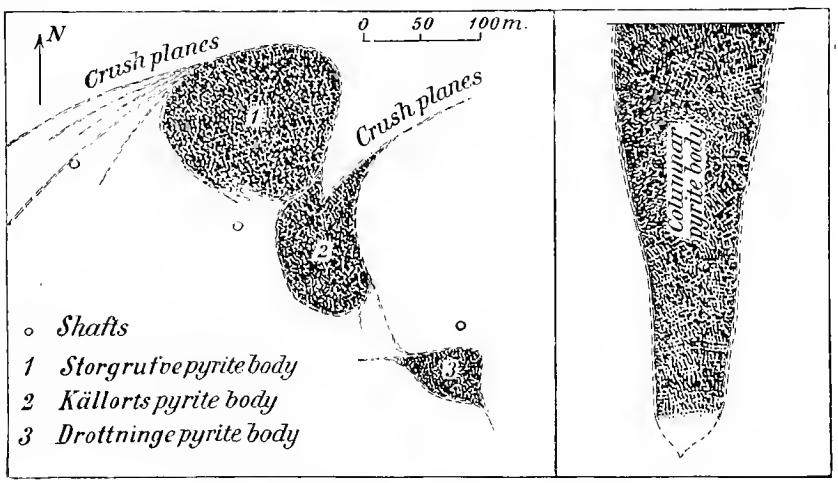

Fig. 216.—The pyrite deposit at Fahlun. Törnebohm.

2. Hard ore, chiefly quartzite impregnated with chalcopyrite to the extent of 3–5 per cent of copper, and pyrite.

3. Rich gold ore, essentially a hard ore traversed by veins of metallic gold and of seleniferous galena-bismuthinite, this mineral having according to M. Weibull [2] the composition $PbS.Bi_2S_3 + PbS.Bi_2Se_3$ with 51 per cent of bismuth and 14 per cent of selenium. The gold is found almost exclusively in the immediate vicinity of the selenium mineral so that by hand-sorting, a selenium ore containing 10–30 per cent selenium is obtained on the one hand, and a gold-ore containing 100–300 grm. of gold per ton on the other.

The soft ore containing on an average 2–3 per cent of copper, 2–3 grm. of gold and about 20 grm. of silver per ton, occurs in very large bodies

[1] 'Die Geologie der Fahlun Grube,' *Geol. Fören. Förh.* XV., 1893.
[2] *Ibid.* VII., 1885.

bounded by crush-planes, as illustrated in Fig. 216. These however pinch out at a depth of about 350 m. The other ores occur in the country-rock adjacent to the pyrite masses.

Törnebohm in 1893 regarded the soft and hard ores as sediments which, subsequent to their deposition, had been altered by folding, dislocation, and the intrusion of eruptive rocks. Vogt considers the entire formation as epigenetic. The occurrence of auriferous veins in connection with pyrite masses and impregnations is particularly interesting. It may be regarded as an intermediate type between this group of pyrite deposits and certain gold-quartz lodes.

The Fahlun mine which has been worked continuously since the year 1220 has produced about 500,000 tons of copper, 15 tons of silver, and 1·5 tons of gold, the total value of this production being about 57 millions sterling. The zenith of its prosperity was in the seventeenth century when in the year 1650 no less than 3455 tons of copper were produced. From that time the production has declined till latterly it has been approximately 300 tons of copper per year contained in copper-sulphate, and some 30,000 tons of poor pyrite used for the manufacture of sulphurous and sulphuric acid. The gold production which began in 1881 and rose in 1898 to 109·8 kg. has fallen again so considerably that in 1907 it reached only 26·1 kg.

Pyrite Deposits at Rio Tinto

LITERATURE

Joaquin Gonzalo y Tarin. Descripción fisica, geológica y minera de la Provincia de Huelva. 3 parts. 1886–1888.—Ferd. Römer. Zeit. d. D. Geol. Ges., 1872, 1873, 1876.—J. H. Collins. 'On the Geology of the Rio Tinto Mines,' Quart. Jour. London, XLI., 1885.—L. de Launay. 'Mémoire sur l'ind. du cuivre dans la région d'Huelva,' Ann. des mines, 8. XVI., 1889.—F. Klockmann. 'Über die lagerartige Natur der Kiesvorkommen des südlichen Spaniens und Portugals,' Akad. d. Wiss. zu Berlin, 1894. Zeit. f. prakt. Geol., 1902, 1904.—J. H. L. Vogt. 'Das Huelvakiesfeld,' ibid., 1899.—C. Schmidt and H. Preiswerk. 'Die Erzlagerstätten von Cala, Castillo de las Guardas, und Aznalcollar in der Sierra Morena,' ibid., 1904.—B. Wetzig. 'Beitr. zur Kenntnis d. Huelvaer Kieslagerstätten,' ibid., 1906.—H. Preiswerk. 'Über Azualcollar,' ibid., 1906.

This most important district known sometimes as the Huelva district after the Spanish port of that name and sometimes as the Rio Tinto district after the name of the principal river, extends in the southern portion of the Iberian peninsula almost from the Atlantic on the west to the Guadalquiver on the east, following generally the southern slope of the Sierra Morena and that of the western continuation of the Sierra de Aracena, upon which slopes the most important mines between San Domingo in Portugal to the west, and Rio Tinto to the east are found grouped.

By far the largest number of these deposits therefore lie in Spain. The length of the zone, not taking into account the smaller isolated deposits, is about 130 km. and the width about 20 km. The principal occurrences are Rio Tinto, situated about 83 km. from the port Huelva; Tharsis, 45 km. from Huelva; and San Domingo, about 17 km. from the town of Pomaron situated on the navigable river Guadiana. Other important occurrences are: La Peña, Poderosa, Esperanza, San Miguel, La Zarza, Lapilla, etc. Several of the deposits mentioned are indicated on the map, Fig. 217.

The district is traversed by a number of railways most of which start from Huelva and diverge to the north and to the north-east. These are in part special mineral railways but they also include main lines, as for instance that from Huelva north through Zafra to Lisbon and that east through Seville to Madrid or to Cadiz. Farther to the west the district is served by the line which runs from Ajamonte through Faro and Beja to Lisbon. In addition to these, several east-west cross-lines join together different mines belonging to the same company.

The principal features of the geological structure of the district are to be seen from Fig. 217, which is taken from the International Geological Map of Europe. Upon this map the pyrite deposits are indicated by spots of dark colour. The uplands which border on the Huelva flat and which are characterized by soft hills rising from 300 m. to heights of 400 m. or even 500 m., consist of Palæozoic beds interbedded with numerous eruptive rocks and transgressed by others. These sediments strike approximately east-west with a slight trend towards the south-east and have in general a steep dip to the north.

The most careful geological investigation of this district yet undertaken is that by Gonzalo y Tarin, who distinguished an ancient formation upon which the Cambrian, Silurian, and Culm rested. This ancient formation consists of gneiss, mica-schist, quartzite, limestone, and hornblende-schist, while the Palæozoic sediments lying as a covering upon it consist chiefly of clay-slate greatly dynamo-metamorphosed, subordinately of grauwacke, and to a lesser extent of limestone, lyddite, and hornstone. In a few places fossils, recognized in part as Silurian and in part as Culm, have been found though not in sufficient number to settle the stratigraphy of the district, especially as the geological correlation depends in part upon questionable petrographical differences. For instance latterly, Culm fossils were found within rocks previously supposed to be Silurian. According to Klockmann there probably is present an unbroken sequence of Silurian, Devonian, and Culm formations, which have been intensely folded, inverted, and even overthrust.

Among the eruptive rocks, granite, syenite, diorite, porphyry, and

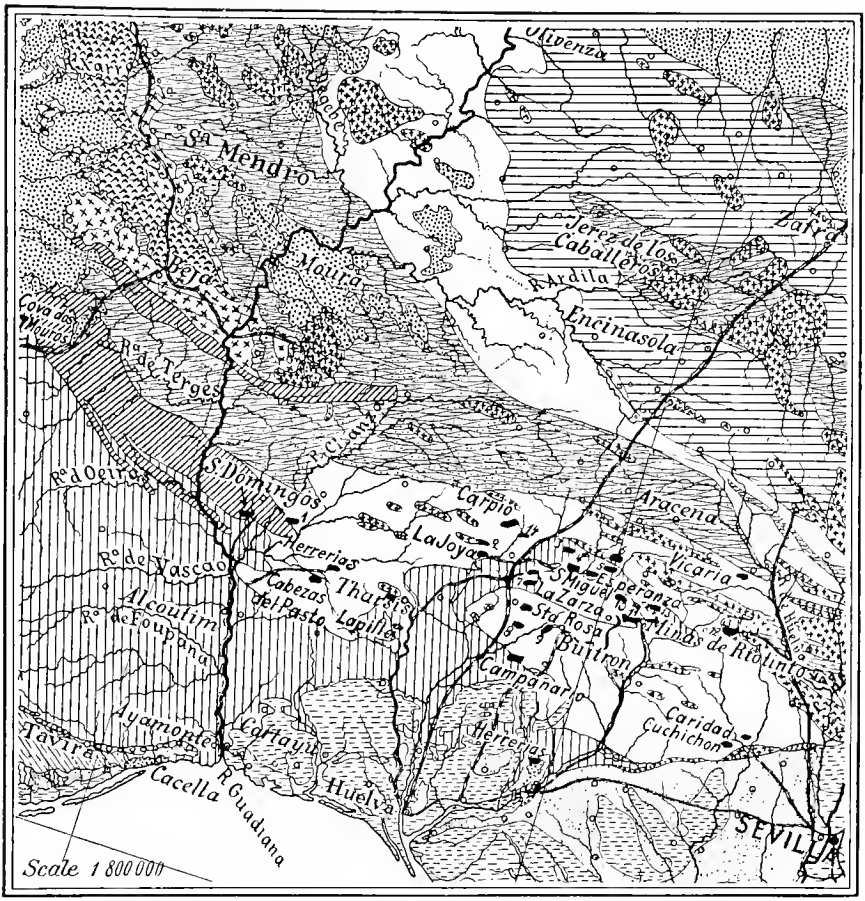

FIG. 217.—Geological map of the Huelva district based upon the International Geological Map of Europe, and showing the position of the following mines:

1, Borranco Trinpancho; 2, Romana; 3, Cueva de la Mora; 4, Monte Romero and Angelica; 5, San Platon; 6, Concepcion; 7, Perunal; 8, Sotiel Coronada; 9, San Pedro and Gloria; 10, Poderosa; 11, Chaparita; 12, Castillo de las Guardas; 13, Peña del Hierro; 14, San Telmo.

diabase are the most frequent. Schmidt and Preiswerk in 1904 described small bosses of granite accompanied by their contact-zones at Cala and in the immediate neighbourhood of the pyrite occurrences at Castillo de las Guardas. Foliated porphyry and porphyrite of variable composition occur extensively throughout the entire district, while quartz-porphyry with about 76·5 per cent SiO_2, quartz-diorite porphyry and felsophyre with 62·6 per cent SiO_2, as well as more basic porphyrite such as diabase-porphyrite with but 40 per cent SiO_2, occur occasionally.

Klockmann considered all these porphyries and porphyrites to be sheets contemporaneous with the sedimentation of the slates and mentioned rocks which he regarded as tuffs. On the other hand Gonzalo y Tarin, and with him de Launay and Vogt, considered that an intrusive origin of these rocks was indicated, a view which Schmidt and Preiswerk have lately definitely established. The occurrences of porphyry and porphyrite, representing between them an almost continuous petrographical series, all appear to belong to the one long-continued eruption and in their entirety to be intrusive. The bedded form which they take is to be explained by their intrusion during plication of the strata. In any case the pyrite deposits are invariably found in the near neighbourhood of these porphyry beds, and most of them, even if not all, occur in the Culm measures and not in the Silurian, as indicated on the map previously mentioned.

The alteration of the country-rock throughout the whole district is very characteristic. Regional-metamorphism appears to have proceeded with contact-metamorphism, this latter being more often remarked in the neighbourhood of the plutonic rocks, while the former has not only left its imprint upon the sediments but also upon the eruptives. To the present it has not yet been determined where stratigraphically the line shall be drawn between the crystalline schists and the Cambrian, nor in how far the first may only be altered sediments. The porphyry often shows a striking kaolinization which it is difficult to explain by the ordinary processes of weathering only, but which is more probably due to thermal effect in connection with younger tectonic phenomena.

The deposits are found both within the eruptives and the sedimentaries as well as at the contact of both. Like the beds enclosing them and as indicated in Fig. 97, they dip steeply and are lenticular in form. This shape, as can be seen in many cases, is not original and it must be referred to subsequent tectonic movements which have affected country-rock and deposit alike.

Among the tectonic phenomena which come into consideration that of plication must receive first mention; it has tilted the beds and given them their general east-west direction. Of no less importance are the transverse faults and overthrusts. The former strike approximately

north-south and dip sometimes to the east and sometimes to the west. They effect the appearance of lateral dislocation which is so extensive in and characteristic of the Rio Tinto district, one result of which may well be that not a few of the deposits now regarded as independent may in truth be but portions of one and the same body first severed by these transverse faults and then thrown out of line, to the north or to the south. Since in many cases an alteration of the ore-body took place at the same time in the neighbourhood of these faults, a lenticular form often resulted in this way.

The overthrusts are quite distinct from the faults. They are to be regarded as the products of plication although they cannot always have marked an end to its operation, but sometimes arose while it was still proceeding. With them the foot-wall was thrust up over the hanging-wall. Under favourable circumstances, where this may have happened more than once, the original width of the pyrite body may have become so affected that greater width of ore-body alternates almost regularly in depth with smaller width, as for instance in the San Miguel mine. In cross section such an occurrence presents the appearance of a sequence of lenses within which it is occasionally still possible to recognize indications of the disturbances to which the increase of width of the deposit is due. It is worthy of remark that overthrusts in ore do not shape their planes in a manner typical of their occurrence in softer rock. While in this they generally form a crushed zone in which only in the rarest case does any open space remain, the plane of overthrust in ore often stands some centimetres open. The difference rests naturally upon the greater resistance, hardness, and brittleness of the ore-bodies. Where these have been subject to intense tectonic movement they must naturally also have suffered intensely in their internal structure. As evidence of this the ore-bodies in many mines are found crushed and reduced to an infinite number of small angular pieces some centimetres in size, forced and kneaded into one another.

The size of these Iberian pyrite deposits whether in strike or dip is very variable.[1] While occasionally the irregular, lenticular, or columnar ore-bodies possess remarkable width and extension in depth, others which may appear important at the surface have at a depth of 200 m. already pinched out, as was the case at El Confessionario and in two cases at Tharsis. In addition a large number of mines show decreasing dimensions in depth. The relations between the length, depth, and horizontal extent of several ore-bodies is given in the following statement :

[1] Vogt, *Zeit. f. prakt. Geol.*, 1899, p. 241.

	Length.	Maximum Width.	Average Surface Width.	Surface Area.	Deepest Shaft 1896.
Rio Tinto—	Metres.	Metres.	Metres.	Metres.	Metres.
Dionisio	1000	150	60–70	65,000	375
South Lode . . .	1100	180	40–60	50,000	300
North Lode . . .	300	100	80	25,000	150
San Domingo . . .	400	75	30–50	15,000	150
Aguas Tenidas . . .	150	75	50	7,000	150

As illustrated in Fig. 115 some mines work more than one ore-body; the Rio Tinto for instance. The South Lode of that mine presents striking differences in width. At the surface this is as much as 180 m. of compact pyrite, from which high figure it decreases to a pronounced pinch at a depth of 100 m., while along the strike it disappears after some hundred metres.

According to experience the general statement may be made respecting the Huelva district that the pyrite occurrences there reach no great depth. So far they have been followed down to 300–400 m., at which depth the decrease in width is considerable.

The horizontal area on the surface of some of these deposits may be seen from the above table. The total area has been estimated to be just under 500,000 sq. m., the significance of which figure will be apparent when it is compared with analogous measurements of other European occurrences; the pyrite deposit of Rammelsberg for instance with approximately 8000 sq. m.

The pyrite deposits of the Rio Tinto district represent not only one of the largest accumulations of copper in the world but at the same time the greatest collection of pyrite. It is probable that originally there was in these deposits altogether from 250 million to 400 million tons of pyrite containing 1–3 per cent of copper. Of this total however a large tonnage has been removed by erosion while some 125 million tons have been mined. Concerning this latter figure it must be remarked that in consequence partly of primary variation in deposition and partly of subsequent enrichment near the surface, this tonnage contained the richest of the copper ore.

The primary ore is chiefly a fine-grained, compact pyrite mass consisting chiefly of pyrite, with some chalcopyrite and small amounts of other sulphides, galena, sphalerite, etc., these latter being however generally not visible to the naked eye. In addition there is some small admixture of quartz the amount of which in places however may increase. At times also streaked or striped patches occur, and in isolated occurrences the pyrite may be banded with galena or sphalerite in such a manner so as to

resemble the 'mixed ore' of Rammelsberg. Often too the ore-bodies consist of a sequence of numerous conformable thicknesses of variable composition ; while finally in the neighbouring schistose country-rock pyrite impregnations resembling fahlbands are found.

Of great scientific interest and of equal economic importance for the Huelva district are the primary and secondary depth-zones which have been demonstrated to occur in connection with the distribution of the metal content in these deposits. By surface weathering the original pyrite, invariably containing more or less copper, has become altered to limonite. With this change the copper content has in most cases become so completely leached that no trace of resultant malachite or azurite can be seen, while even chemical analysis is often unable to offer any evidence of an original copper content. The removal of the sulphur is equally complete, analyses of the gossan generally showing this to be almost completely free from both copper and sulphur.

It would consequently be difficult for a mining engineer or geologist unaccustomed to such conditions, to determine from surface exposures only whether that which he was investigating were a deposit of iron or the gossan of a pyrite deposit. To differentiate between these two possibilities there is but one piece of evidence to which no objection can be taken, namely the nature of the decomposition of the country-rock in the neighbourhood of the deposit. If the deposit in question were originally of pyrite then, by the sulphuric acid resulting from the oxidation of such pyrite, the country-rock would have been robbed of all its original constituents save the quartz. To-day in this secondary iron ore, extremely typical skeleton crystals of quartz are found.

The depth of this gossan, which doubtless one day will be valuable because of the iron in it, is on an average about 20 m., though in places it is more than 40 m. The cementation zone beneath contains chiefly bornite and chalcopyrite, relative to which there is evidence that in the process of cementation, from the cupriferous pyrite chalcopyrite was first formed which then became raised to bornite, the next higher copper sulphide. The sequence of these depth-zones is illustrated in Fig. 12.

The depth of the enriched zone varies in different mines but it may reach as much as 50 m. or more. From it the ore, containing occasionally 10–15 per cent of copper, is derived. This rich ore, which has sometimes been produced in considerable quantities by individual mines, is in some cases prudently kept in reserve in order by calculated addition to bring the copper content of poorer primary ore up to the minimum demanded for export, this minimum being generally 2·5 per cent.

As will be mentioned more particularly when discussing the composition of this pyrite, silver is generally present in amount up to 40 grm. per ton,

while traces of gold are often found. These precious metals in the process of secondary redistribution of the metal content have become concentrated by themselves in a layer but a few centimetres thick at the contact between the oxidation and cementation zones.

Occasionally striking effects of decomposition are seen, such for instance as the occurrence of small pieces of cementation ore well within the primary zone. In such cases it may generally be demonstrated that the level of the ground-water has sunk on both sides of a fissure, whereby the processes of secondary redistribution to which the upper zones owe their existence were carried into the primary zone. Under such circumstances cementation ores rather than those of oxidation become formed, since the mineral solutions circulating in such a fissure become reduced by the pyrite on either side and, following the usual replacement processes, the pyrite becomes first converted to chalcopyrite and afterwards to bornite.

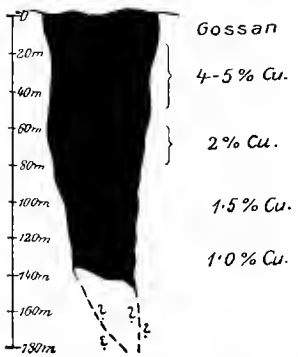

FIG. 218.—Vertical section of the Domingo deposit in the Rio Tinto district showing the decrease of the copper content in depth. Vogt, *Zeit. f. prakt. Geol.*, 1899, p. 249.

In their bearing upon the future of this district the primary depth-zones which the deposits exhibit are of special importance. Experience in the last decades has shown that the average copper content gradually diminishes in depth even in those mines which have long since been operating in the primary zone. While the difference between the copper content of the cementation ore and that of the adjacent upper portion of the primary zone is considerable and may in individual cases be represented by such a proportion as 10 : 3, the decrease with greater depth within the primary zone is quite gradual, requiring a hundred metres or even some hundred metres to bring about a decrease from 3 to 2 or from that again to 1·5 per cent.

The Composition of the Rio Tinto Pyrite.—From the analyses given in the following table it may be seen that the Rio Tinto pyrite, of which the essential constituents are iron, sulphur, and copper, contains other substances and among them, silver and arsenic. The silver content being as before mentioned generally below 40 grm. per ton, may be left out of consideration at present; that of the arsenic however is worthy of further remark. Although the amount of this element is but small it is embarrassing both in the manufacture of sulphuric acid, to which this pyrite is applied, as well as in the application of the residues to the production of iron. In consequence of this small amount of arsenic the pyrite from the Rio Tinto district

is worth somewhat less than that from Norway, a fact which is expressed by a difference of one or two shillings per ton in favour of the latter. In this matter of arsenic the ore from one small mine, the El Tinto, contains 1·5–2 per cent, which is much above the average, while on the other hand that from the Aguas Tenidas, now stopped, exceptionally contained no arsenic though at the same time but little copper.

Analyses of Rio Tinto Ore

	Rio Tinto.				Tharsis.			San Domingo.
	1	2	3	4	5	6	7	8
S . .	49·00	48·50	48·00	47·76	49·60	47·43	44·60	49·30
Fe . .	43·55	40·92	40·74	43·99	42·88	41·30	38·70	41·41
Cu . .	3·20	4·21	3·42	3·69	2·26	3·73	3·80	5·81
Pb . .	0·93	1·52	0·82	0·10	0·52	0·58	0·58	0·66
Zn . .	0·35	0·22	Trace	0·24	0·10	Trace	0·30	Trace
As . .	0·47	0·33	0·21	0·83	0·28	0·33	0·26	0·31
Sb . .	...	...	Trace	...	Trace	0·14	...	Trace
Bi . .	...	...	...	0·37	...	Trace	...	...
Co . .	...	...	...	0·05	...	0·06	...	...
Ni . .	...	...	...	...	...	Trace	...	...
SiO_2 . .	1·70	3·46	5·67	1·99	2·94	3·68	11·10	2·00
CaO . .	0·14	0·90	0·21	0·23	0·18	0·67	0·14	0·14
MgO . .	...	...	0·08	0·07	Trace	0·10	Trace	Trace
O in Fe_2O_3	...	...	0·09	...	0·15	...	0·23	0·25
SO_3 . .	...	...	...	...	...	1·40	...	...
H_2O . .	0·70	...	0·91	0·48	0·95	0·13	0·17	0·05
Total .	100·04	100·06	100·15	99·80	99·46	99·55	99·88	99·93

The average copper content of the whole output is not so high as the figures of the above analyses would indicate. That of the Rio Tinto mine in the 'nineties for instance was about 2·9 per cent, while that of the more important of the other mines ranged from 2·5 to 2·75 per cent. Since then the average has sunk somewhat so that in recent years it may be put down at the highest as 2·5 per cent for the whole district.

In the following table the approximate average content at different depths and in different mines is given. In each case the high content near the surface is doubtless due to secondary enrichment :

[Table

	Depth.	Per Cent Cu.
	m.	
Dionisio, Rio Tinto . . .	40–120	4
	200	2
	350	1·5
San Domingo	20–40	4–5
	60–80	2
	100	1·5
	140	1
Cabezas del Pasto	40	3·5
	60	3
	80	2
Caridad near Aznalcollar . .	40	4–5
	110	0·5

The pyrite of the upper levels often carries some copper and iron sulphates as recent secondary products, and some selenite, etc. The rocks in the immediate vicinity of the ore-bodies, when not completely decomposed, are, in consequence of their saturation with acid water, strongly corroded and in a condition which makes a proper conception of their original character most difficult. The streams flowing from the district are coloured red or brownish-red because of the iron oxide they contain, hence the names Rio Tinto and Aguas Tenidas, the former meaning coloured river and the latter stained water. In the marshes at the river mouths more than 50 km. away from the deposits, considerable accumulations of iron oxide are found, this oxide arising from the secondary sulphates mentioned above.

Some authorities, especially Klockmann but including also Ferd. Römer, Wetzig, Stelzner, and Bergeat, considered these Rio Tinto deposits to be sediments. The conformability between the slates and the pyrite beds, the occurrence of parallel layers in the ore-bodies, and the banding of the pyrite, were facts quoted in support of this view. As mentioned before however the evidences in favour of a sedimentary origin are inconclusive. Even the supporters of this view, Klockmann and later Wetzig, remarked the close connection of the pyrite with the occurrences of porphyry and porphyrite, a connection which they explained in that the outpourings of porphyry brought the constituents of the pyrite with them, iron, copper, etc., on the one side and sulphur on the other, precipitation resulting.

Against this Gonzalo y Tarin, supported especially by de Launay, Vogt, and latterly by Schmidt and Preiswerk, advocated an epigenetic origin. The very irregular shape, well illustrated by the North Lode of Rio Tinto, is difficult to harmonize with a sedimentary formation. In greater part the deposits occur at different horizons of the Culm-measures. Were they then formed by sedimentation, the circumstances of their formation must have been repeated at intervals and at different places. Not

only is it the case that the slates are impregnated with primary pyrite but occasionally also the porphyry. Moreover conformity between pyrite deposit and slate is not invariably the case. For instance the pyrite of San Miguel, according to Beyschlag and Krusch, and that of Aznarcollar, according to Schmidt and Preiswerk, cut across the slate in places and it was particularly remarked that at both localities this was actually the case, and not an appearance due to false schistosity. Other similar transgressions of the pyrite across the slate have also been described. With this fact established an epigenetic origin to these deposits must be concluded.

The absence of druses may, as with the Norwegian deposits, be because the pyritic material was not deposited gradually, like for instance the material of the lead-silver lodes, but all at once, to crystallize later. The folding of the slates, the intrusion of the porphyry, and the formation of the pyrite, were probably, as suggested by de Launay, all connected and consecutive phases of one inclusive occurrence. The arguments for consolidation from magmatic solutions and for the source of those solutions from rock magmas, quoted in connection with the corresponding deposits in Norway, may in their essence be applied to these of Rio Tinto.

Mining in this district began originally as far back as the time of the Phoenicians, that is about the eleventh century B.C. or perhaps still earlier, from which date it continued almost without break to the eighth century A.D. in which period is included a time of great activity during the Roman occupation. At that time the small secondary veins of rich copper ore within the pyrite mass were more particularly worked, and the larger bodies became riddled, as with mole holes, to a depth of some 125 m. During the Moorish occupation the mines were idle. In the sixteenth century some of the mines were started again though to the middle of the last century operations continued on but a small scale. Thus the annual production between the years 1783 and 1849 was generally 80–150 tons of metallic copper, though occasionally it was more than 200 tons. Only in the 'fifties and 'sixties did the present large-scale production begin; San Domingo for instance in 1856, Tharsis in 1866, and the present Rio Tinto Company in the beginning of the 'seventies. The production since then may be gathered from the figures on pp. 303, 326, and 327.

[TABLE

	Total Output of Pyrite, Rio Tinto Company.				Ore treated at the Mine.		Copper recovered.
	Shipped.	For treatment at the Mine.	Total.	Average Copper content.	Long Tons of Pyrite.	Average Copper content.	Long Tons.
1888	434,316	969,317	1,403,633	2949	393,149	2208	18,522
1890	396,349	865,405	1,261,754	2883	397,875	2595	19,183
1892	406,912	995,151	1,402,063	2819	435,758	2569 1465	20,017
1894	498,540	888,555	1,387,095	3027	485,441	2594 988	20,606
1896	591,752	845,580	1,437,332	2931	549,585	2529 1068	20,817
1898	644,518	820,862	1,465,380	2852	618,110	2600 1023	20,426
1900	704,803	1,189,701	1,894,504	2744	665,967	2553 1187	21,120
1901	633,949	1,294,827	1,928,776	2627	641,935	2680 1025	21,100
1902	627,967	1,237,322	1,865,289	2517	595,092	2342 1495	21,659
1903	688,919	1,229,619	1,918,538	2390	667,748	2320 1241	21,565
1904	672,344	1,276,475	1,948,819	2340	663,744	2105 978	21,218
1905	627,336	1,202,768	1,830,104	2363	660,724	2182 1124	19,530
1906	655,328	1,268,388	1,923,716	2411	632,307	2302 1198	21,287
1907	641,858	1,265,090	1,906,948	2417	607,944	2112 1048	21,251
1908	604,275	1,115,610	1,719,885	2265	589,815	2037 952	24,256

According to Gonzalo y Tarin the amount of ore won from these deposits previously was altogether about 30 million tons containing 1·2 million tons of copper, figures which the *Mining Journal*, London, Feb. 1894, and August 1895, put at 20 million tons and 0·8 million tons respectively, the authority in the issue of the latter date being W. G. Bowie, who also estimated that up to the end of 1894 modern mining had produced about 58 million tons of ore. To these figures some 40 million tons may be added as the production from that date till the end of 1908, up to which date it would therefore appear that about 125 million tons of ore had been mined. The output of ore and the production of copper from Rio Tinto in later years are given in the above table which is taken from *The Mineral Industry*, 1908.

The total pyrite production of Spain and Portugal in recent years has been as follows:

	Spain.	Portugal.
	Metric tons.	Metric tons.
1900	2,750,000	402,870
1901	2,700,000	443,597
1902	2,760,000	413,714
1903	2,947,500	376,177
1904	2,786,000	463,731
1905	2,805,123	352,479
1906	2,888,778	350,746
1907	3,182,645	351,000

According to the yearly statistics of Merton & Co. the following amounts of copper were produced from the pyrite of the Rio Tinto district during the years given :

	1880.	1890.	1895.	1900.	1905.	1909.
Rio Tinto	16,215	30,000	33,500	35,732	32,280	35,370
Tharsis	9,151	10,300	12,500	7,965	4,345	4,355
San Domingo	6,603	5,600	4,100	3,460	2,720	2,365
Sevilla	1,705	810	1,050	1,460	1,280	1,820
Other mines	2,639	4,990	4,300	4,255	4,185	8,275
Totals (Long Tons) . .	36,313	51,700	54,950	52,872	44,810	52,185

From these figures it will be seen that the production rose steadily to about the year 1895 since when, in spite of the larger quantity of ore mined, it has fallen somewhat, consequent upon the decrease in copper content in depth. The largest of these deposits are worked in opencut to a depth of 100–120 m., below which depth ordinary mining supervenes.

Pyrite Deposits of Sain Bel and Chessy in France

LITERATURE

L. de Launay. 'Die Schwefelkieslagerstätte von Sain Bel (Rhône),' Zeit. f. prakt. Geol., 1901.

The only deposits worked for pyrite in France are at Sain Bel in the Rhone department about 20 km. north-west of Lyon. These deposits occur in a practically continuous zone which strikes north-south and which, by scattered outcrops, appears to be connected with the classic though exhausted occurrence at Chessy some 10 km. farther to the north.

From the accompanying sketch taken from the geological map published by Michel Lévy and used by de Launay, it appears that the deposit at Chessy is associated with pre-Cambrian felspathic schists, while at Sain Bel the deposits are connected with chlorite- and hornblende-schists of uncertain age and origin.

At Chessy the schists are impregnated with pyrite containing as much as 6–12 per cent of copper, with some quartz and barite. Mining began in this district as far back as the Roman time. In the year 1809 the mine was already 215 m. deep and showed then a considerable diminution of the copper content. Presumably the zone of secondary enrichment had by that time become exhausted. The pyrite in these pre-Cambrian schists consisted in part of a bronze-coloured mixture with 6 per cent of copper, and in part of chalcopyrite with 15–20 per cent. Quite by accident some driving was done in the sandstone and shale of the Keuper formation lying to the east. In these, when in the neighbourhood of the pre-Cambrian schists, veins of melaconite, malachite, and azurite, were found, the output from which for a time caused a considerable increase in production. In addition to the pyrite bodies and the copper veins an impregnation zone of azurite nodules in the Keuper sandstone was followed for 150 m. along the strike and 30 m. in dip with a width of 5 m. From this zone the nodules of copper carbonate so often seen in collections were derived.

The pyrite occurrence at Sain Bel carries both lode-like and lenticular masses. The present production comes from a lens worked at St. Gobain, the so-called *Grand Filon* of Bibost, and from another lens at St. Antoine. The lode at Bibost, which is in fact a lens, has a length of 600 m. and a width of 14–20 m. so that 1 m. of height gives 60,000 tons of ore. This contains 50–52 per cent of sulphur. The horizontal section is approximately double that of Rammelsberg. To a depth of 166 m. no diminution of thickness has been experienced, and the total quantity of ore in the deposit has been estimated at 13 million tons. This pyrite mass, excluding the occurrence at Fahlun which is now almost exhausted, is the largest of all occurrences in Europe other than those in the Iberian Peninsula. It consists of compact pyrite similar to that of Rio Tinto but with less admixture of impurities, so that the ore sold may be guaranteed to contain 50 per cent of sulphur. The demarcation between the compact unstriped pyrite and the chlorite schists is definite and sharp although on both sides these schists are to some extent impregnated with pyrite. It is important to observe that apart from some dykes of quartz-porphyry seen at some distance striking at right angles to the pyrite zone, no eruptive rock occurs in the district. The origin of the hornblende-schist is as mentioned before uncertain. These occurrences are undoubtedly epigenetic and in many respects present resemblances to those at Rio Tinto. The composition of the pyrite may be seen from the following analyses, I., of the lens of St. Gobain, and II., that of the *Grand Filon.*

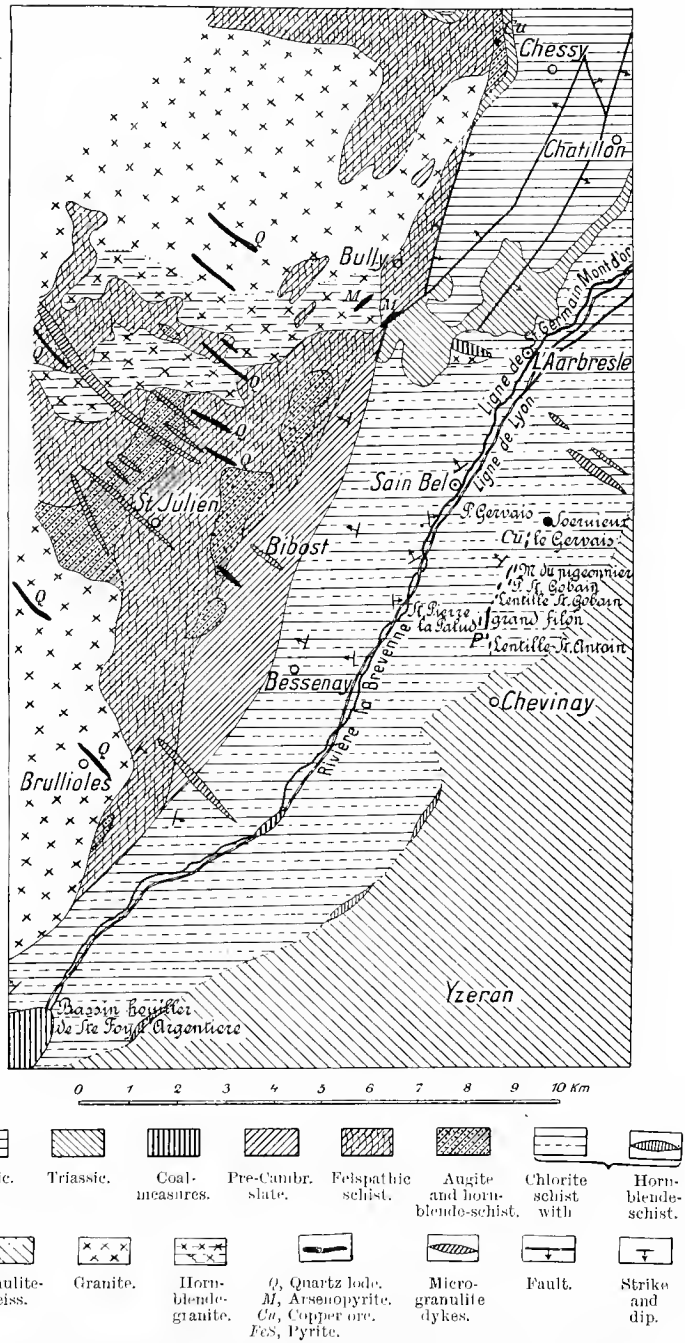

FIG. 219.—Geological map of the neighbourhood around Sain Bel and Chessy. Michel Lévy, *Zeit. f. prakt. Geol.*, 1901.

	I.	II.
Sulphur . . .	53·09 per cent	52·49 per cent
Iron	46·46 „	46·43 „
Gangue . . .	0·37 „	0·90 „
Arsenic . . .	Traces	Traces

The pyrite is practically without copper and contains but little quartz. The Société de Saint-Gobain during the period 1872–1908 produced altogether from Saiu Bel about 7·5 million tons of pyrite, the yearly variations of output being indicated in the statement on p. 303. The other occurrences in France produce an additional 2000 tons per year.

The Pyrite Occurrence at Agordo

LITERATURE

Haidinger. 'Analyse des minerais de cuivre d'Agordo,' Bull. Soc. Géol. de la France, 2e, Vol. IV., 1846, p. 164.—Haton de la Goupillère. 'Mémoire sur Agordo,' Ann. des mines, 5e, Vol. VIII., 1855.—B. von Cotta. Agordo. Berg- u. Hüttenm. Ztg., 1862, pp. 425-427.—B. Walter. 'Beitrag zur Kenntnis der Erzlagerstätte von Agordo,' Oesterr. Zeit. f. Berg- u. Hüttenw., 1863, pp. 114-119.—A. St. Schmidt. 'Geognostisch-bergmännische Skizze über den Kiesstock von Agordo,' Berg- u. Hütten. Ztg., 1867, p. 240.—Pellati. 'Relaz. Ind. Miner. Stattist.,' Regno Italia, Firenze, 1868.—Mazzuoli. 'Traitement des minerais par voie humide à Agordo,' Ann. des mines, 7e, Vol. IX., 1879, p. 190.—D'Achiardi. I Minerali, etc., Vol. I., 1883, p. 331.

This deposit lies in the Imperina valley of the Venetian Alps about 15 km. from the frontier with the Tyrol. It owes the frequency of its mention to the interest awakened by the article by von Cotta cited above. The deposit occurs in pre-Carboniferous micaceous clay-slates which are separated from the Triassic beds and the overlying Lias of the Alps by a well-marked dislocation termed the Agordo-Cormelico fault. The Triassic beds therefore have no bearing upon the deposit which is exclusively connected with the micaceous clay-slates associated with the Permian quartz-porphyries. These slates in the neighbourhood of the pyrite bodies are light-coloured and to a distance of about 30 m. much silicified. Farther away however they pass to dark graphitic schists with bright divisional surfaces. In these dark schists inclusions of pyrite are found.

The deposit generally speaking has the shape of a long extended and flattened lens which strikes south-west and north-east and of which the axis dips at an angle of 20° to the north. It comes to surface in the bed of the Imperina River where its outcrop can be traced for a length of about 460 m., with a width which varies from 4 to 30 m. Mining operations underground have proved a length of 550 m., a width which reaches as much as 39 m., and a present depth of 200 m.

The mass of the deposit consists of pyrite with a little quartz and with definitely banded chalcopyrite. In places where the quartz is particularly plentiful other minerals occur, such for instance as galena, sphalerite, löllingite, argentiferous tetrahedrite, linnaeite, arsenopyrite, ullmannite, etc. Calcite is seldom seen. Goslarite occurs as a decomposition product.

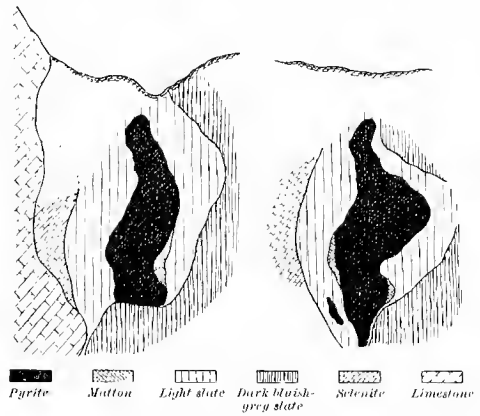

FIG. 220.—The pyrite deposit of Agordo. B. von Cotta, *B-u. H-Ztg.*, 1862, p. 425.

The ore is compact though the bodies show a banding which is generally parallel to the walls. Three classes of ore are distinguished, rich pyrite with 4–30 per cent of copper; medium ore with 2–4 per cent; and poor ore with 0·5–2 per cent. Reckoned over the entire output the average copper content will probably be about 1·7 per cent.

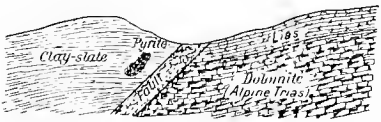

FIG. 221.—Geological position of the pyrite deposit of Agordo; diagrammatic. Bibolini.

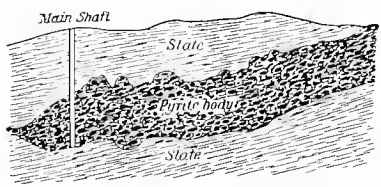

FIG. 222.—Section of the pyrite deposit of Agordo; diagrammatic. Pellati.

The genesis of this deposit has not yet been satisfactorily established. It is pre-Triassic and presumably Permian. In all probability it is the product of magmatic differentiation within an acid magma. The above-mentioned Agordo-Cormelico fault influenced deposition to this extent that it probably brought the pyrite, already formed and concentrated in depth, into the vicinity of the contact between the porphyry and the clay-slate.

The output from Agordo for a long time amounted to some 200 tons of

copper per year, though from this figure it has since receded. The total quantity of ore within the probabilities of the deposit has been reckoned at 1·75 million cubic metres from which however it is probable that the best ore has been already extracted. To-day the deposit is regarded as unpayable. L. de Launay about the year 1890 estimated the ore reserves then at 176,000 cubic metres.[1] The mine belongs to the district of Vicenza, which district in the year 1908 [2] produced altogether 28,860 tons of pyrite, of which 27,000 tons were stated to be cupriferous. The total value of this production amounted to about £21,000 or equivalent to 14s. 6d. per ton.

The Pyrite Occurrence of Ghinivert

LITERATURE

V. Novarese. 'La Miniera del Beth e Ghinivert,' Rass. Miner., Vol. VII., March 1900. Turin, 1900.

Within the mass of the mountain known as the Punta del Ghinivert, situated within the municipalities Pragelato and Massello, cupriferous

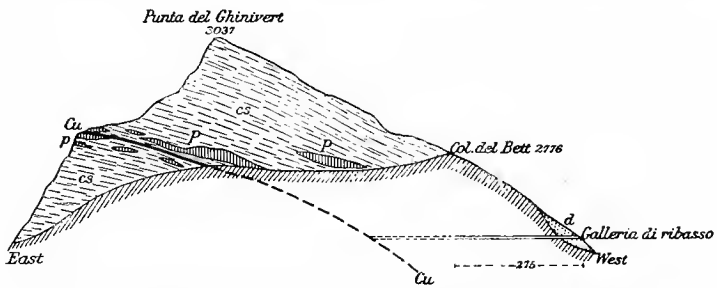

Fig. 223.—The pyrite deposit at Ghinivert. V. Novarese, *Rass. Miner.* Vol. VII.

cs, Calcareous schist; *Cu*, cupriferous pyrite; *p*, euphotide or gabbro.

pyrite deposits occur which in their geological relation exhibit great similarity to those of Agordo.

The above-mentioned mountain consists of calcareous schists in which, analogous to the Norwegian occurrence, lenticular masses of euphotide or gabbro-rock occur. It is in the immediate neighbourhood of this rock that the deposits of pyrite are found. These for the present however are without economic importance.

[1] *Traité des gîtes minéraux et métallifères.*
[2] *Rivista del servizio minerario*, Rome, 1909.

The Pyrite Deposits of Schmöllnitz

LITERATURE

Freiherr von Andoran. 'Die Erzlagerstätten des Zipser und Gömörer Komitats,' Handb. d. k. k. geol. Reichsanstalt, 1859.—A. Hauch. 'Schmöllnitzer Hüttenprozesse,' Oesterr. Zeit. f. Berg- u. Hüttenw., 1860, pp. 269-271.—B. von Cotta. Die Lehre von den Erzlagerstätten, 1860, Pt. II.—B. von Cotta und L. von Fellenberg. Die Erzlagerstätten Ungarns und Siebenbürgens, 1862.—G. Faller. 'Der Kupferbergbau in Schmöllnitz,' Berg- u. Hüttenm. Jahrb. d. k. k. österr. Bergakad., 1868, pp. 193-197.—von Hauer. Erläuterungen zu Blatt III. der geologischen Übersichtskarte der k. k. österr.-ung. Monarchie.—J. Steinhausz. 'Der Kupfer- und Schwefelkiesbergbau von Schmöllnitz,' Berg- u. Hüttenm. Jahrb. d. k. k. österr. Bergakad., 1896, pp. 267-320.—Fähndrich. 'Der Schwefelkiesbergbau bei Schmöllnitz,' Zeit. f. d. B-, H- u. S.-Wesen im preuss. Staat, 1898, pp. 217-234.—F. Schafarzik. 'Daten zur genauen Kenntnis des Szepes-Gömörer Erzgebirges,' Ungar. Math. u. Naturw. Ber. Vol. XXIII., Pt. 3, Leipzig, 1905.—H. Böckh. 'Beiträge zur Gliederung des Szepes-Gömörer Erzgebirges,' Jahresber. d. k. ung. geol. Reichsanstalt für 1905, pp. 46-53, etc.

The counties of Zips and Gömör in Hungary are famous for their many lode-like deposits of siderite and bedded deposits of pyrite which occur in close connection with basic eruptive rocks. The particular hills in which they are found are known as the Zips-Gömörer Erzgebirge. Schmöllnitz lies in a deep tributary valley which coming from the north enters the main Göllnitz valley.

The main features of the geological structure of the country are according to Böckh as follows: The Zips-Gömörer Erzgebirge consist in greater part of graphitic schists and quartzitic sandstones belonging to the Culm which have been foliated and folded by dykes of quartz and quartz-porphyry. In the vicinity of the deposits the rocks are silicified and given a dioritic facies. It is only in places that rocks representing the Carboniferous Limestone occur. The upper Carboniferous beds above consist of quartzitic schists, conglomerates, and lilac-coloured clay-slates with small impure coal seams. These beds are covered by Permian quartzites which have a wide extent in the iron districts. A still younger covering consisting of Werfen beds, Triassic limestones, and Lias, is found in places. The Palæozoic beds have been folded into east-west synclines and anticlines in such a manner that at Schmöllnitz the anticlines are of Carboniferous beds while the synclines consist of Permian quartzite.

The ore-deposits themselves are found chiefly in a greyish-green zone of talcose, chloritic, sericitic, or quartzitic schists, which zone, rich in quartz, strikes east-north-east and dips 60–80° to the south. Between the two hills Rotenberg and Spitzenberg a complex of light-coloured sericitic and quartzitic schists over 400 m. in width occurs within a mass of dark graphitic schists. Within this light complex are interbedded:

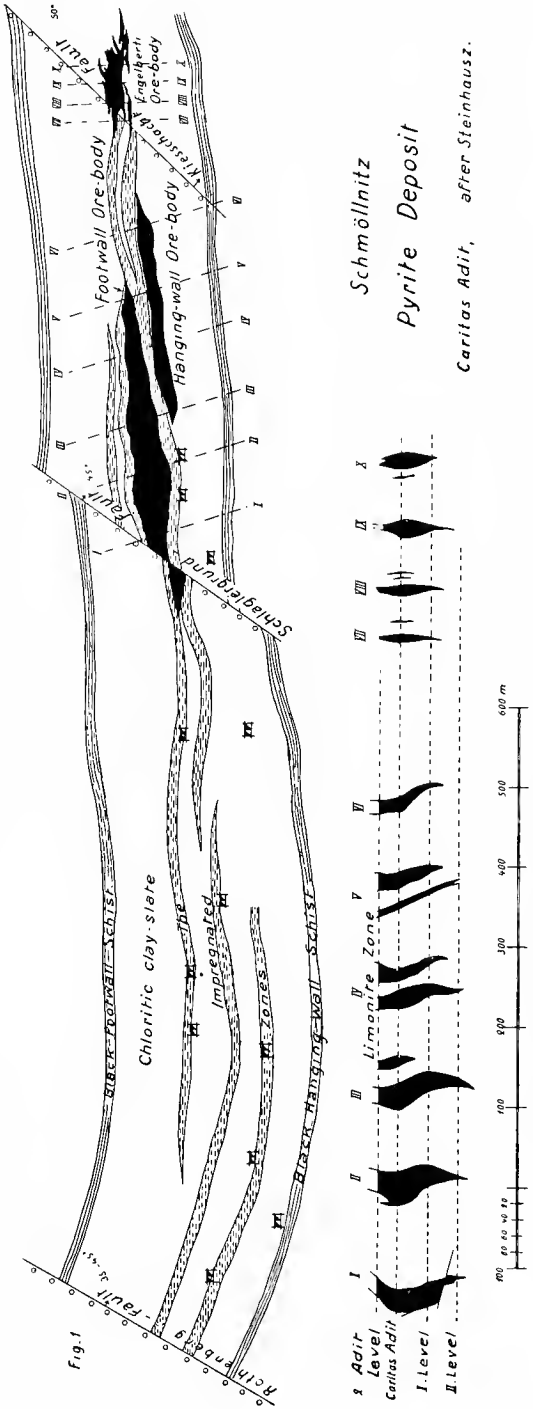

FIG. 224.—The Schmöllnitz pyrite deposit; horizontal section through the Caritas Adit, after Steinhausz.

1. Impregnated zones resembling fahlbands.

2. Lenticular pyrite bodies.

Of the former three are known, namely the hanging-wall, the middle, and the foot-wall zones, between which, large clean ore-bodies occur parallel to the formation. These zones can be followed for as much as 4 km. in length, to a depth of over 400 m., and each with a width of almost 20 m. The individual pyrite bodies are naturally of less extent. That termed the foot-wall body however is known to extend for more than 600 m. along the strike, for more than 140 m. along the dip, and to possess a thickness up to 40 m.; the Engelberti body has dimensions of 300 m., 80 m., and 30 m. respectively; and the hanging-wall body 260 m., 80 m., and 15 m. respectively. In depth however it may be said that these deposits in general do not maintain their importance.

The separation between the pyrite and the country-rock is not always sharp. The ores

are sometimes banded, in places massive, and where they approach their walls they are contaminated by schistose material. The principal ore is pyrite; chalcopyrite occurs chiefly in pockets, bornite more often in thin layers, while sphalerite and galena seldom occur. The sulphur content is moderate.

Although large faults are in general uncommon they nevertheless occur, and it would appear that in the neighbourhood of such dislocations the copper content is higher. This may likely be due to a secondary redistribution of the original content, since with the copper other younger sulphides, such for instance as sphalerite and galena, appear. In the central portions of the deposits the average copper content is 0·5 per cent, an amount which increases towards the margins until at the actual periphery it is about 2 per cent.

The genesis of these pyrite deposits has been dealt with by both Steinhausz and Fähndrich. The former considers them of epigenetic nature on account of the local association with diorite. Fähndrich on the other hand, on account of their conformability to the surrounding rocks and of the banding of the ore, regards them as sedimentary ore-beds. This was the view generally held formerly. Recent investigation in which Böckh took a prominent part, has shown without doubt that those deposits to which attention has latterly been paid are in close relation to the occurrences of basic eruptive rock. This association has indeed become so established that in searching for such ore-deposits the first step taken is to locate the presence of basic eruptive rocks. It is of interest to note that petrographically these rocks resemble the saussurite-gabbro associated with the Norwegian pyrite masses.

The composition of the pyrite from Schmöllnitz, where mining began as far back as the thirteenth century, may be seen from the following analyses, while some idea of the yearly production since 1884 may be gathered from the table on p. 303.

Analyses of Pyrite from Schmöllnitz according to Steinhausz

S	47·89	Bi	0·03
Fe	45·31	Ni and Co	Tr
Cu	0·46	Mn	Tr
Zn	0·37	CaO	0·03
Pb	0·33	MgO	0·05
As	0·55	Undetermined	4·89
Sb	0·06		
		Total	99·07

The Pyrite Deposits of Graslitz-Klingental, etc., in the Saxon-Bohemian Erzgebirge

LITERATURE

B. von Cotta. Berg- und Hüttenm. Ztg., 1869.—C. Gäbert. 'Über Graslitz,' Jahrb. d. k. k. geol. Reichsanstalt, 1899; 'Über Klingental und Graslitz,' Zeit. f. prakt. Geol., 1901.—R. Beck. 'Kieslagerstätten im sächsischen Erzgebirge,' ibid., 1905.—B. Baumgärtel. 'Über Klingental,' ibid., 1905.—O. Stutzer. 'Alte und neue geologische Beobachtungen an den Kieslagerstätten Sulitjelma-Röros-Klingental,' Österr. Zeit. f. d. Berg- u. Hüttenw., 1906; Zeit. f. prakt. Geol., 1909, p. 133.

These deposits lie near the frontier between Saxony and Bohemia, Graslitz being in Bohemia and Klingental in Saxony. In addition to the curious occurrence in a crosscut of a door sealed by the customs authorities marking the boundary between the two countries, the deposits are

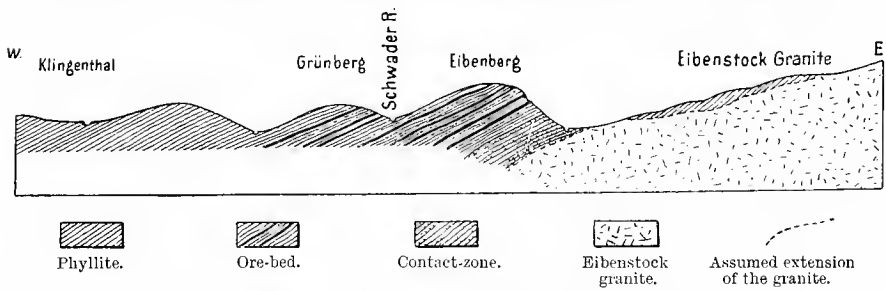

Fig. 225.—Section of the Graslitz-Klingenthal pyrite beds.
Gäbert, *Zeit. f. prakt. Geol.*, 1901, p. 141.

also worthy of remark in that the copper content allows only such a bare profit to be made that the mine management is constantly confronted with the struggle for existence.

The occurrences lie to the north of Graslitz on the two hills Eibenberg and Grünberg in an eastward projecting tongue of the phyllite formation which there forms a thin patch upon the granite. The beds usually lie with a north-south strike and a dip of 20–30° to the west, so that when going in this direction, successively higher horizons of the phyllite are encountered. This formation on the two hills mentioned consists of a lower portion of quartzose and felspathic phyllites, and an upper portion of a more slaty character. In these beds the ore-deposits occur as conformably interbedded layers 0·5–3 m. in thickness.

The ore-bodies consist of a quartz-slate rock impregnated with ore. In the quartz the ore is found as irregular pockets, stringers, and impregnations, while in the slate it occurs chiefly on the bedding-planes but also irregularly distributed in veins and impregnations. In width such bodies

are usually small though in places this dimension may be more considerable. They occur one overlying the other and separated by barren widths of 25 to 250 m., ten of such ore-bodies having been exposed by mining operations. The extension along the strike is considerable, the ancients in the adit known as Michaelstollen having followed the occurrence for a total length of 3000 m. The ore consists chiefly of the sulphides, pyrrhotite, pyrite, chalcopyrite, and arsenopyrite, though to a less extent the richer copper and other sulphides are found.

Several theories of genesis have been advanced for these deposits. Gäbert, Beck, and Baumgärtel, laid emphasis on the association of the ore with movement-planes or disturbed zones. Gäbert considers that the impregnation with pyrite obviously took place in a slate zone which, similar to the occurrence described on p. 310, had been dynamically altered. According to von Cotta, Gäbert, and Beck, these pyrite deposits in spite of their conformity are epigenetic in nature; while Stutzer, going farther than this, considers they are magmatic intrusions like the corresponding occurrences in Norway.

Among the ores, pyrrhotite and chalcopyrite are of particular importance. According to unpublished work by Krusch, the pyrrhotite occurrence must be discriminated from that of the other minerals. The massive bodies of that mineral he regards as older and presumably intrusive members of the rock-complex; while the chalcopyrite, occurring in veins and pockets having no relation to the bedding of the complex, is of distinct vein-character.

On an average the ore contains 9–10 per cent of sulphur and about 1–1·3 per cent of copper. To suit the fine distribution of these contents an acid process devised by Schlenzig was applied, with the result that a concentrate with 22 per cent of sulphur was obtained. In the year 1907 the monthly output of ore was 1000–2000 tons, but normally a yearly output of 36,000 tons of ore may be reckoned.

The Intrusive Fahlbands

LITERATURE

E. Weinschenk. 'Die Kieslagerstätten im Silberberg bei Bodenmais,' Abh. d. kgl. bayr. Akad. d. W. II. Kl. Vol. XXI., Pt. 2, 1901; 'Der Silberberg bei Bodenmais,' Zeit. f. prakt. Geol., 1900.—K. Gruber. Abh. d. bayr. Akad. d. W. II. Kl. Vol. XXI., Pt. 2, 1901.—W. von Gümbel. Geognostische Beschreibung des ostbayrischen Grenzegebirges, 1868, und Geologie von Bayern, 1864.—J. Lehmann. Untersuchungen über die Entstehung der altkristallinischen Schiefergesteine, pp. 175-178. Bonn, 1884.—Thiel. Beitrag zur Kenntnis der nutzbaren Mineralien des Bayrischen Waldes. Diss., Erlangen, 1891.

These deposits, among which that of Bodenmais in the Bavarian forest may be regarded as typical, may appropriately be treated here.

At Silberberg near Bodenmais, at the foot and on the south side of the Arber mountain, 1458 m. high, fahlbands, well-known on account of the variety of minerals they contain, are found in cordierite- or cordierite-garnet-gneiss overlying a large granite area. According to Weinschenk whose careful presentation is here in greater part followed, this is not typical gneiss but a contact metamorphic rock which owes

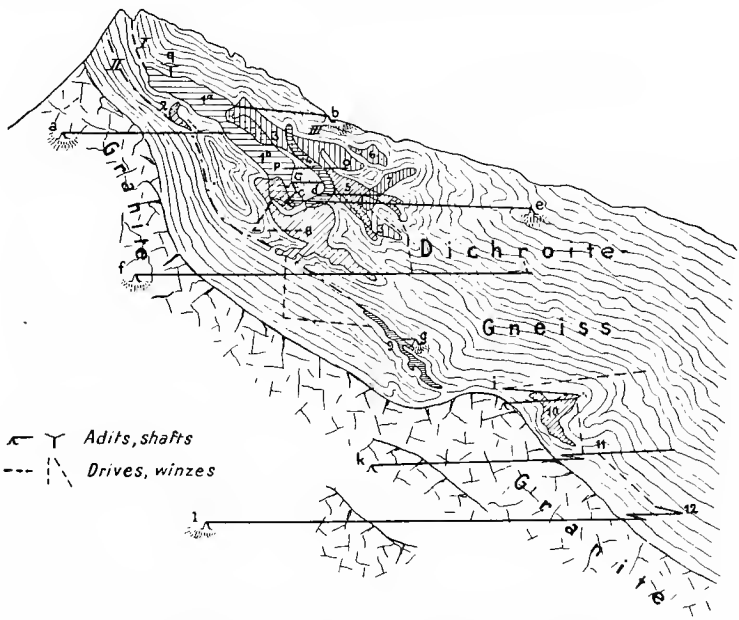

FIG. 226.—The Bodenmais pyrite deposit. Gümbel.

I, Main ore-bed; *II*, foot-wall leader; *III*, hanging-wall leader; 1-12, stopes, opencuts, or standing ore; a-l, tunnel buildings, shafts, etc.

its present appearance to the intrusion of the granite and to the infiltration of the granitic magma.

This peculiar rock in certain beds is sprinkled with pyrite which mineral in places becomes so concentrated that payable ore-bodies result. Generally speaking these are lenses with irregular outline, occurring conformably at different horizons in the gneissic rock but never far from the granite beneath. It is further remarked that the ore occurs where two varieties of this rock come into contact, for instance where hard rock resembling hornstone on one side comes into contact with micaceous rock often triturated and broken on the other. In Norway, as mentioned on p. 309, the pyrite occurrences are often found under similar circumstances.

The most important ore minerals are pyrrhotite, pyrite, chalcopyrite, sphalerite, and galena. Cassiterite only occurs in places, but then in fairly large amount. Magnetite also is found, while the occurrence of kreittonite, the zinc-spinel, is particularly interesting. The pyrrhotite is practically without nickel, contains very little cobalt, and but small amounts of gold and silver. The galena contains 0·44–0·52 per cent of silver which was formerly recovered, hence the name of Silberberg.

The most important gangue minerals are quartz, cordierite with pinite, andesine or oligoclase, orthoclase, biotite, hypersthene, brown hornblende, andalusite, etc. In addition, zeolites, spessartite, vivianite, selenite, barite, etc., are found as secondary products. The width of ore is generally one or two metres though in places it reaches 22 m.

Because of the general bedded character of these deposits they were formerly regarded as the sediments of some ancient sea. Lehmann in 1884 however argued an epigenetic and intrusive nature, a view afterwards supported in detail by Weinschenk who showed that the ore-bodies at times cross the bedding and enclose angular fragments of the country-rock so as to form breccia. These facts may be considered to prove that the ore is younger than its country-rock.

The view that they were deposited from aqueous solution or formed by pneumatolytic phenomena cannot, in the complete absence of drusy cavities, be maintained. Weinschenk, as evidence of consolidation from magmatic solution, laid stress on the fact that a regular sequence in the separation of the constituents from such a magma could be recognized. The chalcopyrite, just as with the pyrite deposits of Norway, most pronouncedly occupies the interstices between the other minerals and was therefore the last to separate. The gangue minerals, quartz, hypersthene, cordierite, etc., when found within the ore, have their crystal angles rounded and generally their surfaces corroded. The quartz too has the double pyramid either entirely without or with only a short prism, characteristic of igneous origin and similar to the habit of quartz in quartz-porphyry. According to Weinschenk the deposits are therefore to be regarded as products at the consolidation of a molten mass forced up from below. As stated on p. 278, the mutual solubility of sulphide and silicate rises with the temperature, so that with increasing temperature silicates may hold more sulphides in solution and sulphides more silicates. The material of the idiomorphic crystals of quartz, hypersthene, etc., which separated out of the sulphide solution, was certainly originally dissolved in the sulphide magma.

The rocks adjacent to the ore-bodies are often bordered with a layer of sphalerite and impregnated with zinc-spinel. Where the texture of these rocks is an open one, all the cracks, for instance those within the

felspar, are also coated with this same spinel, which is certainly of secondary formation arising according to Weinschenk from the action of zinc-sulphide upon such aluminous minerals as biotite, sillimanite, felspar, etc., just as zinc-spinel is formed in the retorts of zinc-furnaces, a formation studied by Stelzner and Schulze.[1]

Mining at Bodenmais is of great antiquity having been mentioned as far back as 1364. Latterly the ore has been used exclusively for the production of vitriol and *potée*, this latter being the elutriated iron-oxide used in glass polishing. For this purpose the yearly output has varied between 1900 and 2900 tons of pyrite. Similar deposits long exhausted were formerly worked at Daxelried and Unterried to the north-west, and at Lam to the north of Bodenmais.

Many deposits hitherto classed with the fahlbands have in greater probability been formed by the intrusion of molten sulphide material along bedding-planes. Thus Vogt regards the fahlbands of Kongsberg as of such formation and these are the most typical example of all fahlbands. Of similar formation are many of the deposits of chalcopyrite and pyrite found in the crystalline schists. Some of these are important, as for instance the copper deposits of Åtvidaberg-Bersbo in south-east Sweden, described by A. E. Törnebohm,[2] which from 1764 to the cessation of work a few years ago produced a total of about 35,000 tons of copper.

At present however it is not possible to separate from one another those deposits which have hitherto been regarded as fahlbands. It is therefore regarded as preferable to deal later and under this name with all the various fahlbands which, though they may be of different genesis or their genesis may still be in question, have all at least many morphological characters in common.

C. METAL SEGREGATIONS

1. Nickel-Iron in Peridotite and Serpentine

Awarnite, a variety of nickel-iron consisting of 67·93 per cent Ni, 0·70 Co, and 31·02 Fe, and corresponding therefore almost exactly to the formula Ni_2Fe, was discovered by G. H. F. Ulrich [3] in a primary deposit in peridotite and associated serpentine, on the west coast of New Zealand, over a wide district between the Cascade River and Awarua Bay. Before this, nickel-iron had been known to occur in secondary deposits. It had also been found as a primary deposit in serpentine in the Alps,

[1] *Neues Jahrbuch f. Min.*, 1881, I. [2] *Geol. Fören. Förh.* VII., 1885.
[3] *Quart. Jour.* XLVI., 1890.

at the summit of the Riffelhorn near Zermatt, by Miss E. Aston and T. G. Bonney,[1] though proper details of this occurrence are wanting. In the river beds of the Josephine and Jackson Counties of Oregon, W. H. Melville [2] found, in the form of boulders up to more than 100 lbs. in weight, a nickeliferous iron, josephinite, which chemically approaches very closely to awaruite. Its composition corresponds practically to the formula Fe_2Ni_5, a little of the nickel being replaced by cobalt, while copper and arsenic are also present in small amount. It is accompanied by chromite, serpentine, etc., and sometimes is seen in blocks of serpentine, from which fact it may be concluded that the primary deposit was undoubtedly an olivine rock. A. Sella mentions a nickel-iron with 75·2 per cent of cobaltiferous nickel and 26·6 per cent of iron, or approximately Fe_3Ni_8 or $FeNi_3$, in the auriferous sand of the river Elvo near Biella in Piedmont.[3]

2. Nickeliferous Iron in Basalt

The large blocks of nickeliferous iron up to 25 tons in weight found by A. E. Nordenskiöld during the years 1870 and 1871 at Uifak on the island of Disko, off the west coast of Greenland, created considerable discussion. These were found upon a large basalt sheet. In addition nickeliferous iron has been observed by K. J. V. Steenstrup in the adjacent basalt, a felspar basalt, and in basalt at other places in Greenland. This iron, long used by the Eskimos for their implements, generally contains 1·5 to 2·75 per cent of nickel, 0·3 to 0·8 cobalt, and 0·12–0·40 copper. It is further almost invariably accompanied by 1·2–4 per cent of carbon partly in the form of graphite and partly as carbon in combination with the iron. The iron found in basalt is often accompanied by cohenite Fe_3C, schreibersite $(Fe,Ni,Co)_3P$, pyrrhotite, anorthite, pinel, etc.

Nordenskiöld regarded the above-mentioned blocks as meteorites which fell simultaneously with the extrusion of the basalt in Miocene time. Later investigation however has shown that they are undoubtedly metal reduced from the oxides of basalt magmas. In explanation of such a reduction it may be conceived that the basalt magma in question repeatedly broke through or flowed over beds of lignite or other organic substance. The inclusion of fragments of such material could have effected the reduction of the iron and the still more complete reduction of any nickel, cobalt, or copper present, since, as indicated on p. 153, these metals are more readily brought to the metallic condition than iron.

The comprehensive bibliography of these iron deposits of Greenland finds mention in most mineralogical and petrographical text-books and

[1] *Quart. Jour.* LII., 1896, p. 453. [2] *Am. Jour. Sc.*, 1892 and 1905
[3] *Comp. Rend.* CLII., Paris, 1891, p. 171.

more particularly in the *Lehrbuch der Mineralogie* by Hintze. Reference may also be made to *Mineralogia Groenlandica*, by O. B. Böggild, Copenhagen, 1905, and to a paper by A. Schwantke upon the iron of Uifak, in the *Sitzungsber. d. Preuss. Akad. d. Wiss.*, 1906.

Metallic iron has also been found in other basalts, as for instance at Antrim in Ireland, at Rowno in Wolhynien, near Weimar in the neighbourhood of Cassel; and in addition it has been observed in other basic intrusions and sheets.

The famous chemist Cl. Winkler[1] suggested the possibility that the separation of metallic nickel and iron resulted from the presence of volatile metal carbonates such as $Ni(CO)_4$, $Fe(CO)_5$, and $Fe_2(CO)_7$, which become dissociated at comparatively low temperatures. This hypothesis finds however no support in the natural appearance of the metals concerned.

The discoveries of nickel-iron, of nickeliferous iron, and perhaps in some cases also of metallic iron without nickel, sometimes in basic plutonic rocks and sometimes in the corresponding intrusions or sheets, though always of no economic importance, are of particular interest in that they form a terrestrial analogy to the cosmical meteorites.

3. Platinum in Peridotite

LITERATURE

J. F. Kemp. 'Geological Relation and Distribution of Platinum and Associated Metals,' U.S. Geol. Survey, Bull. 193, 1902.

The platinum metals, ruthenium, atomic weight 101·7, rhodium 103, palladium 106·5, osmium 191, iridium 193, and platinum 194·8, have hitherto only been won from detrital deposits or gravels. The heaviest natural mineral is platinum or iron-platinum which generally consists of 70–86 per cent of platinum, 8–18 per cent iron, a low percentage of other metals especially osmium and iridium, and a small amount of copper. After platinum come, osmiridium or iridosmium containing a little iron, iridium, iridium-platinum, and palladium. Allopalladium, the hexagonal modification of palladium, is found as a great rarity in a lode in diabase at Tilkerode in the Harz. Finally, mention must be made of sperrylite $PtAs_2$, and laurite, RuS_2.

Platinum was first discovered in 1755 in the auriferous sand of the river Pinto, in the province of Choco, Columbia. Until recently it has been known to occur only in detrital deposits in which deposits it has been found in the Urals, from whence the greatest output of the metal is obtained; in Columbia; near Rio Abeate in British Columbia; at Minas

[1] 'Möglichkeit der Einwanderung von Metallen in Eruptivgesteine unter Vermittlung der Kohlenoxyd,' *Sächs Akademie der Wissenschaft*, Leipzig, 1900.

Geraes, Brazil ; and in New Zealand, Borneo, etc. At all these places the iron-platinum is found associated with a considerable amount of chromite, magnetite, and the decomposition products of peridotite.

The platinum gravels of the Urals, those on the Tulameen River in the south-western portion of British Columbia and elsewhere, occur either in areas of fresh or decomposed peridotite or in the rivers which flow from such areas. The metal is found in nuggets intergrown sometimes with chromite, more seldom with fresh or decomposed olivine, and exceptionally with pyroxene. Here and there also it is found associated with osmiridium and with gold. Kemp, after examination of several nuggets, was able to state that the chromite crystallized somewhat earlier than the iron-platinum which has a somewhat lower fusion point, while the olivine on the other hand only separated after the crystallization of the platinum was complete.

From the above considerations the conclusion was drawn by G. Rose as far back as 1842 that the parent rock of the iron-platinum and of the associated minerals must in most cases have been a peridotite, and further that the platinum occurred in close association with chromite or chromite deposits. This conclusion was substantiated at the commencement of the 'nineties by the discovery in the Urals at a place in the Solourieff Hills in the district of Goroblagodatsk, of primary platinum scattered throughout a somewhat decomposed olivine rock which also contained pockets or nests of chrome-iron. Material taken from the prospecting trenches, at most but a few metres deep, gave 22 grm. of coarse platinum dust per ton, while laboratory tests upon material taken from the ore pockets gave as high as 93–110 grm. of fine dust per ton of rock.[1] In Beck's *Lehre von der Erzlagerstätten* it is mentioned on the authority of S. Conradi that new discoveries of native platinum in olivine-rock have been made in the Urals.

The occurrence of platinum metals in fresh olivine and the crystallization sequence mentioned above, undoubtedly justify the conclusion that iron-platinum and osmiridium are the products of magmatic consolidation, while from their association with chromite it follows that within peridotite magma, at all events in places, minute amounts of the platinum metals were subjected to a magmatic differentiation in common with the chromite components. Further evidence of the magmatic origin of platinum has been obtained by Beck [2] as the result of investigation by metallographic means upon the structure of native platinum.

[1] A. Inostranzeff, *St. Petersburg Naturw. Ges.*, Nov. 7, 1892 ; translated by Kemp in the above cited work. A. Saytzeff, *Die Platinlagerstätten am Ural*, Tomsk, 1898 ; reviewed *Zeit. f. prakt. Geol.*, 1898, p. 395 ; 'Geol. Untersuchungen im Kreise Nikolai-Pawdinsk,' *Arb. des Kais. Russ. Geol. Komitees*, St. Petersburg, XIII. 1. R. Helmhacker, *Zeit. f. prakt. Geol.*, 1893, p. 87. R. Beck, *ibid.*, 1898, p. 25. R. Spring, *ibid.*, 1905. E. Hussak, 'Über Vorkommen von Palladium und Platin in Brasilien,' *ibid.*, 1907.

[2] *Bericht d. Ges. d. Wiss.* LIX., Leipzig, 1907.

Stanislas Meunier, taking another view, regards the occurrences of native platinum, those of the iron found on the island of Disko, and those of the chromite deposits, as formed by pneumatolytic processes[1] wherein the chlorides of platinum, nickel, iron, chromium, etc., played important parts. The conclusions of Meunier however are founded chiefly upon laboratory experiments and not, or only to a small extent, upon actual observation of the deposits in question. It is considered however that in no case can the chromite deposits be explained by pneumatolysis, nor is there any support to be found for the view that awaruite, nickel-iron, or the platinum metals were thus formed, but on the contrary the evidence is regarded as indicating that all these occurrences are of purely magmatic origin.

Although the platinum metals preferably associate themselves with eruptive rocks they are however, as pointed out particularly by Kemp, occasionally found in small amount in other rocks and with deposits of other ores. For instance, the copper ore of the Rambler mine in Wyoming contains a small amount of platinum as sperrylite, while in Australia there is the striking occurrence of platinum in the ashes of a certain gas-coal.

In the Urals, by far the most important platinum district in the world, three different localities may be outlined. Of these the first and the most important lies in the neighbourhood of Nishni-Tagilsk and in greater part on the west slope of the Urals, while the other two are found on the east slope; one, comprising the river beds of the Iss and the Dyja, being centred around Goroblagodatsk and Bissersk; and the other around Nicholai-Pawdinsk. At Nishni-Tagilsk the gravels are eluvial, that is they have been formed *in situ* by the removal of the lighter particles of the decomposed parent-rock, the heavy particles remaining exposed or covered with débris. The platiniferous ground covering approximately 180 square versts is centred around the hill Solowjewa and distributed along the valleys of the Martjan, Wissym, Tschaush, Syssimka, etc. The country there consists of gabbro, diorite, serpentine, and a gneissic granite, these rocks being overlaid in places by limestone of Devonian age. The deposits discovered in 1825 produced from that date to the year 1844 somewhat more than 31,693 kg. of platinum, a figure which by 1895 had reached 90,440 kg. The not-inconsiderable differences in yearly output are explained not only by the variable content of the gravels of which the richest are now exhausted, but also from the varying market price of the metal. Thus in 1869 about 2107 kg. were obtained, in 1874 more than 1290 kg., in 1882 something above 1700 kg., in 1886 more than 1325 kg., in 1893 1260 kg., while in 1895 something above 1030 kg. was won.

[1] *Bericht des VII. Internationalen Geologenkongresses*, St. Petersburg, 1897, p. 157.

The gravels in the neighbourhood of Goroblagodatsk are centred around the hills Katschkana 886·2 m. in height, and Sarannajy 656·8 m. These deposits, discovered in the tributaries of the Iss in 1825, have only been energetically worked since the 'sixties. While the production in 1869 was but little above 325 kg., in 1879 it rose to over 650 kg., in 1882 to over 1640 kg., in 1886 to 2290 kg., and in 1893 to 2940 kg., since when it has fallen somewhat.

In the Bissersk district energetic operations also began in the 'sixties from whence in the 'eighties the production rose to about 325 kg., in 1891 to 835 kg., falling back again in 1893 to something above 650 kg.

The price of platinum fifty years ago was only £30 to £35 per kg., or but one-fourth that of gold. Since then however, though subject to much variation, it has gradually risen. In 1900 it reached that of gold, beyond which it still continued to rise till the price was one-third higher than that of gold. Latterly however it has receded to about £160 per kg., that of gold being about £135. The value of the world's annual production now amounts to about one million pounds sterling while that of gold is about 87·5 millions.

The platinum deposits in the Urals produce altogether about 95 per cent of the total production, their contribution between the years 1824 and 1894 being about 123·5 tons, or not quite 2 tons per year. In 1894 the production was 5·215 tons rising in 1901 to 6·328 tons. In these gravels, nuggets are occasionally found which very exceptionally have weighed as much as 9·62 kg. Further details of these platinum deposits will be found in the section dealing with gravels.

4. Native Copper and Native Gold in Eruptive Rocks

LITERATURE

Prof. H. Schulze in H. Kunz, Chile und die deutschen Kolonien. Leipzig, 1890. Julius Klinkhardt.—W. H. Weed. Bull. Geol. Soc. Am., 1903, Vol. XIV.—R. Daintree. 'Note on certain modes of occurrence of gold in Australia,' Quart. Jour. XXXIV., 1878.—K. Schmeisser. Die Goldfelder Australasiens, 1897, p. 92. Dietr. Reimer, Berlin.—F. W. Voit. 'Übersicht über die nutzbaren Lagerstätten Südafrikas,' Zeit. f. prakt. Geol., 1908, p. 14.

In the literature many cases are quoted where gold and copper are said to occur as primary constituents in eruptive rocks. Since however the amounts are always small, sometimes even microscopic, it is extremely difficult to determine whether these minute particles are really primary or whether they have not been introduced by secondary infiltration along ducts which remain unrevealed in the microscopic slide. The first demand and sign of a primary condition is that the particular eruptive rock should be absolutely fresh and that around the metallic particle in question, whether

it be gold or copper, not the slightest trace of decomposition may be observed. The description of these occurrences is limited to that of the following cases.

The Cordilleras of Chili, according to investigation by H. Schulze, include granite with a gold content. The actual words of the description do not however allow it to be said with certainty whether Schulze put much value on the demonstration of a primary condition for this gold. Again, according to W. H. Weed, gold occurs in aplite dykes in the Winskott mine near Helena, Montana. Since however in the same description the relationship of these dykes to pegmatitic quartz lodes is mentioned, and the genesis of this class of quartz lode has not yet been satisfactorily settled, this case is also not free from objection. The occurrences of auriferous pyrite in diorite in Queensland, described by Daintree, are also doubtful. In these occurrences veins of auriferous quartz and pyrite are found both in eruptive rock and at the contact of such rock with Devonian strata, so that a secondary infiltration of pyrite appears very well possible. According to Daintree, C. Wilkinson mentions similar occurrences in those goldfields of New South Wales which occur in Devonian and Upper Silurian beds; while in the catalogue of the museum in Melbourne where he is curator, G. Ulrich describes a specimen of diorite as being auriferous, though it is evident from microscopic examination of this specimen that it must at the same time have been closely associated with gold-quartz veins. According to Schmeisser, north of the mouth of the Richmond River in Australia a scoraceous auriferous basalt occurs lying upon a hard compact variety of the same rock and covered in turn by a columnar equivalent. With reference to this occurrence Beck in his book points out that the gold present may have arisen from auriferous sand and gravel taken up by the basalt magma in its course.

With copper, indisputable cases of its occurrence as a magmatic product are still more rare. The famous deposits of Lake Superior, those in the neighbourhood of Christiania, and those on the Färoe Islands, with all of which native copper occurs in basic rock, are as mentioned elsewhere, certainly younger than the eruptive rock in which they are found, which rock either exercised a reducing effect or conceivably brought about precipitation of the copper by means of some electric property. In his review of the useful deposits of South Africa, F. W. Voit describes a dyke of syenite in crystalline schists in Zululand where hornblende and felspar enclose flakes of native copper. A similar deposit, also perhaps free from objection, has been stated by Schlenzig to occur in New Guinea, where a basic eruptive rock similarly contains flakes of native copper.

Between the various classes of magmatic deposits which have now been differentiated and described there are, as will be seen from the cases

mentioned below, a number of chemical connecting-links. Chromium, while characteristic of the chromite deposits, also occurs in small quantities in many titaniferous-iron ores. Nickel and cobalt, while inseparable associates of pyrrhotite in magmatic deposits, occur also in nickel-iron and nickeliferous iron; in addition they appear as accessory constituents in the intrusive pyrite deposits and have further been shown to occur in some titaniferous-iron ore. Copper, while particularly characteristic of the pyrite deposits, is always found likewise in the nickel-pyrrhotite deposits. In this connection it is interesting to remember that a low copper content has also been established for the nickel-iron of Disko Island and for native platinum. Platinum, while occurring chiefly as iron-platinum, is also characteristically present in small amounts in nickel-pyrrhotite while in addition it has been shown to occur in meteorites, as is also the case with chromium. The primary deposits of platinum indeed appear to be closely associated with those of chromite. Niccolite and chromite are found together in one deposit.

It is not impossible that other deposits, and perhaps even whole classes whose genesis it is now sought to explain in some other way, may in truth have arisen by magmatic differentiation. This is more particularly possible with deposits which since their formation have suffered considerable deformation so that no proper conception of their original character is any longer possible. On the other hand some authorities regard as magmatic segregations deposits which we consider were formed otherwise. Both Beck and Bergeat for instance give in their text-books under the term 'eruptive deposits' a cassiterite deposit at Etha Knob in the Black Hills, Dakota, where the tinstone occurs with spodumene, apatite, triphylite, columbite, tantalite, beryll, etc., in a pegmatitic granite. These minerals are so characteristic of the ordinary occurrence of cassiterite that the whole occurrence is regarded as having been formed by pneumatolysis at a certain stage during the consolidation of the granite. Since therefore the processes of pneumatolysis played the essential part the deposit cannot be classed with those formed directly by magmatic differentiation. The circumstances of the cryolite deposits of Ivigtut and those of the apatite lodes in the trachyte of Jumilla, Spain, both of which deposits Bergeat places with his group of eruptive deposits, are similar. Concerning the term 'eruptive deposit,' we consider that this is less appropriate than that of 'magmatic segregation,' because as the pneumatolytic phenomena are also undoubtedly of eruptive nature it leads to confusion.

CONTACT-DEPOSITS

In contra-distinction to the still extensive application of this term to cover such deposits as occur along the contact of one rock with another of different character, only those deposits, exomorphic or endomorphic, will be considered here which occur within the contact aureole surrounding a consolidated eruptive mass, and which in space, time, and origin, are associated with contact-metamorphism. This definition of these deposits has already been elaborated on pp. 35 and 178-180.

The credit for first properly recognizing the nature and significance of contact-deposits belongs to B. von Cotta who concluded his paper *Die Erzlagerstätten im Banat und Serbien*, published in 1864, with the following résumé: "In relation to geological mode of occurrence, to form, and to composition, the deposits here described—those of Banat—agree most with those of Bogoslowsk in the Urals, and somewhat less with those of Schwarzenberg in the Erzgebirge, Rochlitz in Bohemia, Russkitza on the military frontier, Offenbanya in Siebenbürgen, Chessy near Lyon, Rio Tinto in Spain, those in the Apennines, near Christiania in Norway, and Tunaberg in Sweden. All of these may appropriately be placed in a class of contact-deposits." In 1879 a general description of the characteristics of these deposits was given by A. von Groddeck in his text-book under the 'Christiania' type; while later in 1895 their characteristics were further defined by J. H. L. Vogt.[1] Reference may also be made to the works of Th. Kjerulf and B. Lotti, mentioned below, and to the recent article upon contact-metamorphic deposits by O. Stutzer.[2]

Though in the United States this group of deposits was late in becoming recognized, excellent works upon it by American authorities have appeared in recent years. Among these works the following may be mentioned:

W. Lindgren. 'The Character and Genesis of certain Contact-Deposits' in 'Ore-Deposits,' reprinted from Vols. XXX. and XXXI. Am. Inst. Min. Eng., 1902; 'The

[1] *Zeit. f. prakt. Geol.*, 1895, p. 450.
[2] *Ibid.*, 1909.

Copper Deposits of the Clifton-Morenci District, Arizona,' U.S.G.S. Prof. Paper 43, 1905.—W. H. Weed. 'Ore Deposits near Igneous Contacts,' Am. Inst. Min. Eng., October, 1902.—J. Barrell. Geology of the Marysville District, Montana,' U.S.G.S. Prof. Paper 57 1907.—J. F. Kemp. 'Ore Deposits at the Contacts of Intrusive Rocks and Limestone, etc.,' Econ. Geol. II., 1907.—Van Hise. 'A Treatise on Metamorphism,' U.S.G.S. Monograph 47, 1904.

Rocks as the result of contact-metamorphism undergo in many cases a recrystallization without any addition or loss of material, except water and carbonic acid which are expelled. In other cases, and especially within the inner zones of the contact aureole adjoining the eruptive rock, an addition or a loss of material may often be observed. For instance by the addition of SiO_2 and the expulsion of CO_2 from simple limestone, wollastonite may be formed, and from dolomite the mineral diopside. Similarly, garnet, augite, hornblende, epidote, scapolite, etc., may arise by increment of new material.

The re-formation of minerals, especially that occurring along fractures or divisional planes, often results from metasomatic processes. With contact-metamorphic recrystallization, a 'contact-metasomatis' may therefore be discriminated, this term having been suggested by Barrell. In many cases the increment of material consists of ore and particularly of iron ore. In this connection, just as the terms garnetization, tourmalinization, axinitization, and silicification, are recognized as appropriate in their place, so in cases where iron is introduced the term ferrification appears applicable.

Speaking generally, contact-metamorphism is regarded essentially as resulting from the saturation of rocks with the highly heated vapours escaping from a magma, among which vapours that of water plays an important part. Contact-deposits arising therefrom are more frequently found in connection with plutonic rocks, and less often and less extensively with dykes and sheets. Among the plutonic rocks again it is particularly the acid and intermediate members such as granite, syenite, diorite, etc., which provide ore-deposits within their contact aureole; with plutonic rocks of basic character such deposits are much more seldom. This more frequent association of contact-deposits with acid and intermediate rocks is generally held to be because those rock-magmas carry a larger quantity of magmatic water than do the basic equivalents.

In but few cases are contact-deposits found in sandstone, grauwacke, or slate; most of them occur in more or less impure limestone, an association explained by the greater ease with which limestone succumbs to chemical attack. Contact ores consequently are usually found accompanied by those minerals which are characteristic of the transformation of impure limestone, namely by grossularite or lime-alumina garnet, by andradite or lime-iron garnet, by diopside-pyroxenes, by wollastonite, hornblende,

biotite, epidote, vesuvianite, scapolite, calcite, spinel, etc. With these, some quartz is often associated and occasionally some fluorite, tourmaline, axinite, as well as other fluorine- or boron minerals, such for example as datolite, danburite, and ludwigite ($3MgO$, B_2O_3, Fe_3O_4). At Elba and at Kupferberg in Silesia the mineral lievrite also occurs. Finally as a great rarity helvite, a sulphide-silicate, is found. The great similarity of these contact minerals with those found occurring in the celebrated blocks upon Monte Somma, Vesuvius, must here be remarked.

The most important contact ores in the order of importance are: magnetite, specularite, pyrite, the sulphide ores of copper, zinc, lead, etc.; various compounds of arsenic, bismuth, silver, etc.; and metallic gold.

Contact-deposits either occur 'immediate,' that is at the contact of the eruptive rock with the country-rock, or within portions of the country-rock surrounded by the eruptive; or they are 'collateral,' that is they occur within the contact aureole but at some distance from the eruptive. In many cases, as illustrated in Figs. 48 and 49, they appear as beds or masses conformably interbedded. Often too the ore itself is streaked or banded as in Fig. 122, an appearance probably due to the preference with which the mineral solutions attacked those layers, those for instance of limestone, wherein the change was most readily effected. In other cases the alteration proceeding along fissures would form lode-like ore-bodies within the contact aureole. Sometimes, as illustrated in Fig. 50, both forms of deposit, the conformably-bedded on the one hand and the lodes on the other, occurred together in one place.

These deposits, genetically dependent upon the actual mechanical intrusion of the magma as well as upon the material derivable from it, must be distinguished from those other deposits which subsequent to their formation have become altered by contact with an eruptive rock. Were a pre-existing bed, for instance a sedimentary or metasomatic sphalerite or limonite deposit, included within a complex which suffered intrusion by an eruptive magma so that this bed lay in the aureole, it would become changed, without any material addition from the magma. In the case of the two ores mentioned the alteration would be to magnetite with the usual accompaniment of contact minerals. Busz[1] has described the alteration of sphalerite to magnetite along a basalt dyke in the Louise mine, Siegerland. According to F. Klockmann[2] occurrences of such iron deposits as have been altered by contact-metamorphism subsequent to their formation, occur for example where the Devonian formation in the Oberharz with its already existing hæmatite beds, was intruded by Carboniferous granite; at Angers in Brittany also,[3] near Cala in the Sierra Morena, and at Celleiro in the

[1] *Zentralbl. f. Min.*, 1901. [2] *Zeit. f. prakt. Geol.*, 1904, Pt. 3.
[3] Ch. Barrois, *Ann. de la Soc. Géol. du Nord*, 1886, XII.

Asturias. The occurrence at Cala however, though regarded by Klockmann as one where subsequent alteration by contact-metamorphism took place, is regarded by Schmidt and Preiswerk [1] as an original deposit of material within the contact aureole of a small granite mass. Klockmann moreover, basing his views mainly upon the examples mentioned above, asserts in the article cited that all deposits which have so far been considered as forming the group of contact-deposits are but pre-existing deposits altered by contact-metamorphism, and that consequently no separate increment of ore from the magma took place.

This view appears to be erroneous if only because in many districts, for instance that of Christiania, the ore-deposits occur exclusively in the contact aureole of the eruptive rock. With such occurrences the formation of the ore is in regular relation to contact-metamorphism and genetically is quite distinct from the contact-metamorphism of pre-existing deposits. Kemp, as an argument pointing to the introduction of new material with contact-deposits, recently called attention to the fact that the garnet which accompanies contact ores is in places the iron garnet, andradite or aplome, $Ca_3Fe_2Si_3O_{12}$, the iron content of which cannot have been derived from the limestones as these are poor in iron.

Again in the immediate neighbourhood of the contact-deposits the ordinary strata are usually intensely metamorphosed and often contain quite large crystal-individuals of the contact minerals, expressive of the high degree of contact-metamorphism they have suffered. This extra degree, termed by Vogt *potenzierte Kontaktmetamorphose* or 'contact-supermetamorphism,' is doubtless explained in that the vapours issuing from the magma were particularly plentifully introduced into the beds occupying this position.

Contact-deposits are often found traversed by dykes, aschist, and diaschist, of the particular eruptive rock concerned. From this, supplemented by the fact that the ore-deposition in many localities, as for example at Christiania, took place not in the eruptive but exclusively in the country-rock, the conclusion may be drawn that the ore was deposited before the consolidation of the eruptive. In other cases, as for instance in the formation of tin lodes, deposition of ore continued after the crustal consolidation of the molten intrusion. Further, among contact-deposits a number of very important occurrences are included, not only of iron but also of copper, zinc, lead, etc., and indeed even of bismuth. Since the beds of the country-rock contained originally none or but minimal quantities of these last-named heavy metals, the content of such deposits must be derived from the magma itself and in the following manner. The vapours and solutions issuing from the magma laden with combinations of these heavy

[1] *Zeit. f. prakt. Geol.*, 1904, p. 230.

metals, entered under pressure the solid country-rock where under conditions of super-metamorphism the ore was deposited. It must be taken into consideration however that in this process the vapours would at times attack the country-rock and extract certain of its constituents. It is reasonable to suppose that in this manner silica has often undergone solution, and that in the alteration of limestone to wollastonite or of dolomite to diopside, the silica introduced has in many cases not been derived from the magma but from the neighbouring slates or schists.

With some contact-deposits more stages than one in the ore formation may be observed. Before the consolidation of the eruptive rock and in the early stages of that consolidation the ordinary contact-deposits were formed, and later the different lodes, which latter are to be regarded as an immediate consequence of the eruptive activity.

The juxtaposition of contact-deposits and magmatic segregations in any natural system of classification and the close relationship between these two groups in general, are points which arise from the fact that they both take their metal content direct from the magma. The physical and chemical processes operative in the two cases are however widely different. On the other hand the relationship of contact-deposits to the tin lodes is unmistakable. The formation of the tin lodes associated with granite and that of the contact-deposits so often occurring in close connection with granite, are both to be regarded as eruptive effects, in so far that the ore deposited in each case was directly derived from the magma. Since however the associated minerals in one case differ essentially from those in the other, the chemical processes which were operative must again have been quite different. As will be discussed later, in the formation of tin lodes the fluorides play a decisive part. In the contact-deposits on the other hand fluorite is but seldom met. In these latter, scapolite with a small chlorine content is more often found, though in very small amount. The halogens accordingly took part not infrequently in the formation of contact-deposits, though their amount being so small they cannot generally speaking be taken to have had any material influence upon the mineralization. The heavy metals, such as iron, copper, etc., were therefore certainly not present in the vapours combined with the halogens. The form in which they occurred has not been established, perhaps in part it was as carbonates with water.

With some deposits associated with granite, as for instance at Pitkäranta in Finland and Schwarzenberg in Saxony, contact-deposits containing magnetite and various contact minerals on one side, and occurrences of cassiterite with its companion minerals on the other, occur together in one place. From this the inference may be drawn that under certain conditions both classes of pneumatolytic or pneumatohydatogenetic pheno-

mena can pursue their course independently yet in time and space more or less together.

The minerals present in contact-deposits are not always entirely the same but may occasionally vary. Apart from the ore which usually exceeds all the other minerals in amount, garnet, augite, and hornblende are the most frequent, while epidote and wollastonite are more seldom. In some cases however these two latter minerals equal the other silicates in amount, while certain deposits, among them being that at Campiglia Marittima in Italy,[1] contain lievrite, different pyroxenes, quartz, calcite, fluorite, and epidote, but no garnet. These differences according to Bergeat may perhaps be referable partly at least to the temperature obtaining at the time of formation. Those deposits which were formed immediately at the contact with the intrusive rock are particularly distinguished by garnet, pyroxene, and hornblende, while those farther removed more particularly contain the hydrous silicates, epidote, and lievrite, the formation of which probably does not necessitate so high a temperature. Wollastonite as is well known [2] plays the part of a geological thermometer, since its formation at a pressure of one atmosphere is only possible below a temperature of 1180°, a limit which under greater pressures is doubtless raised. In general it may be taken that the contact-deposits were formed at temperatures above the critical temperature of water, 375° C.

Sedimentary rocks which have suffered contact-metamorphism, even those situated in the immediate vicinity of the intrusive mass, still plainly show their original bedding so that in spite of the nearness of the molten magma, the temperature operative has not been high enough to fuse these rocks.

Bergeat [3] in the year 1909 suggested 'apomagmatic' and 'perimagmatic' as qualifying terms, the first for ores and minerals whose heavy-metal content was extracted, no matter how, or issued from a magma and was deposited at a distance, while the second was for such deposits as settled in the immediate vicinity of the intrusive mass. To the first class would belong in our opinion not only the contact-deposits as here defined as well as the cassiterite and apatite lodes, but also a whole number of other occurrences, as for instance those of quicksilver and many of gold, silver, lead, copper, etc.

The iron deposits occurring in the fundamental rocks at Arendal in Norway, and at Persberg, Dannemora, etc., in Middle Sweden, have in relation to their genesis been variously regarded by different authorities. Those of Arendal according to Vogt are contact-deposits and under that heading they will here be described, while those of Middle Sweden, though

[1] Bergeat, *Neues Jahrb. f. Min.*, 1909.

[2] Allen and White, *Am. Jour. Sc.* XXI., 1906.

[3] *Loc. cit.*

in reality they may include deposits of various genesis, will be treated in the annex to this section.

Among contact-deposits the oxide deposits, such as those of magnetite and specularite, may be differentiated from the sulphide deposits or those containing iron, copper, zinc, and lead, though this division is by no means sharp. While in some contact areas, as for instance in Elba, in the Spring district of Utah, etc., the deposits are almost exclusively of oxide-iron ore, and in others, as for instance in Arizona, they are chiefly sulphide ores of copper, etc., nevertheless in many cases, as for instance at Christiania, in the Banat, and in the Urals, both classes of ore occur so intergrown that in one and the same district some mines are worked for iron while others are worked for copper, zinc, and even for bismuth.

Some contact-deposits attain very considerable dimensions. The copper occurrences in Arizona for instance, which according to Lindgren belong to this class, are among the most important copper deposits in the world. The iron deposits of the Urals which are equally of contact-metamorphic origin are likewise very important.

OXIDE CONTACT-DEPOSITS

The iron deposits of this class wherever they occur are, so far as present experience goes, distinguished by an almost complete absence of titanic acid and generally by the smallness of the amount of manganese present. On the other hand the amounts of pyrite and of sulphur may be considerable. Apatite usually only occurs in traces, though exceptionally, as in the Urals, it may be more plentiful. In the Spring district, Utah, the phosphorus content of the iron ore varies between 0·05 and 3·18 per cent with an average of 0·2 per cent.

Christiania District

LITERATURE

Th. Kjerulf. Die Geologie des südlichen Norwegens. German translation by A. Gurlt. Bonn, 1880.—J. H. L. Vogt. Norske Ertsforekomster, I., 1884; Archiv f. Math. og Naturv., IX.; Geol. Fören. Förh. XIII., 1891, pp. 687-735; Norw. geol. Landesunters., No. 6, 1892; Zeit. f. prakt. Geol., 1894, p. 177; 1895, p. 154; Problems in the Geology of Ore-Deposits, Vols. XXX. and XXXI; Amer. Inst. Min. Eng., 1902.

The post-Silurian and most probably Devonian granite and nordmarkite of this district, particularly where they abut upon beds of Silurian age, are, as shown in Fig. 147, surrounded by a number of contact-deposits. The geology of these intrusive rocks has been exhaustively studied by W. C. Brögger, who used the term 'nordmarkite' for a sodium-quartz-syenite.

These contact-deposits are essentially of iron ore, magnetite in the first place but also specularite. In some cases however they contain either sphalerite, galena, chalcopyrite, or bismuthinite, or a mixture of all of these. More than one hundred small iron mines have been worked here at various times though all are now almost completely stopped. Latterly important deposits of sphalerite,

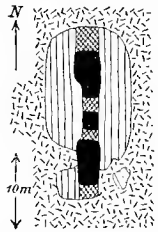

FIG. 227.—Plan of a small prospect at Svenskeskjärpet near Skreia. Vogt.

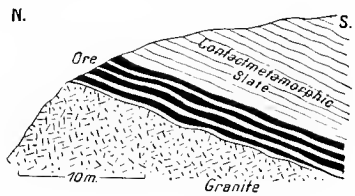

FIG. 228.—Section of the Narverud iron mine in the neighbourhood of Drammen. Vogt.

or sphalerite and galena, have been discovered near Hakedal, north of Christiania, and others of bismuthinite near Kjenner, east of that town. Concerning the position of these various deposits relative to the granite and nordmarkite, Vogt in 1891 gave the following figures. Of 108 different mines and prospects 17, equivalent to sixteen per cent, occurred in areas of Silurian beds completely surrounded by granite, such areas, as illustrated

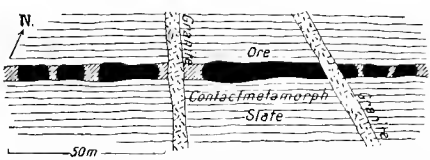

FIG. 229.—Geological position at the Nyberg iron mine near Skreia, showing the deposit traversed by dykes of granite or quartz-porphyry. Vogt.

in Fig. 227, generally being small; 22, or twenty per cent, occurred either immediately at the contact of the granite with the sediments or within a distance of 20 m. from it, as illustrated in Fig. 228; 48, or forty-four per cent, were found farther away, generally 50–250 m. from the contact though exceptionally as much as 1500 m.; while the remainder, or twenty per cent, were found near the intrusive rocks in the fundamental schists or in the pre-granite sheets of porphyry close to the granite or nordmarkite.

Within the contact aureole the deposits are distributed over a number of horizons in the Silurian beds, though outside of this aureole, apart from one or two unimportant occurrences near other eruptive rocks, they are completely wanting. The deposits here cannot therefore be regarded as

metamorphosed pre-existing deposits, but must be held genetically to stand in the closest relation to the granite and nordmarkite intrusions. Keilhau as far back as in the 'thirties made this observation, though he regarded the granite as an alteration product of the Silurian beds. The deposits never occur actually in the granite nor in the nordmarkite but, apart from occasional occurrences in the old porphyry sheets, exclusively in the neighbouring Silurian beds. Even the smallest patch of these Silurian sediments found surrounded by granite often contains considerable quantities of such ore. The ore derived from these intrusive rocks, whether of iron, zinc, lead, or bismuth, was deposited while the intrusive was still in a magmatic condition.

The Banat in Southern Hungary

LITERATURE

B. von Cotta. Erzlagerstätten im Banat und Serbien. Vienna, 1864.—G. Marka. 'Einige Notizen über das Banater Gebirge,' Jahrb. d. k. k. geol. Reichsanstalt, Vol. XIX., 1869.—Castel. 'Mémoires sur les mines du Banat,' Ann. des mines, 6e sér., XVI., 1869.—E. Suess. Zukunft des Goldes, 1877, p. 258; Antlitz der Erde, Vol. I., 1885, p. 210.—J. Szabo. Földt. Közl. VI., 1876.—Hj. Sjögren. 'Beitrag zur Kenntnis der Erzlagerstätten von Moravicza und Dognacska im Banat,' Jahrb. d. k. k. geol. Reichsanstalt, XXXVI., 1886. Also in Geol. Fören. Förh. VII., 1885.—J. Halaváts. 'Bericht über die in den Jahren 1887–1890 in Südungarn bewerkstelligten Detailaufnahmen,' Jahrb. d. Ungar. geol. Anstalt.—P. Rozlozsnik und Koloman Ernszt. 'Beiträge zur genaueren petrographischen und chemischen Kenntnis der Banatite des Komitats Krasso-Szörény,' Jahrb. d. Ungar. geol. Anstalt, Vol. XVI. Pt. 4. p. 190.

In the western portion of the Krassó-Szörényer district, that is the Banat, Mesozoic sediments belonging in general to the Jurassic and the Cretaceous formations are found lying upon what are perhaps Archæan mica-schists and gneisses. The younger sediments, forming synclines long extended in a north-south direction, are ruptured by a powerful zone of disturbance which can be followed approximately in the one direction for more than 100 km. It is supposed that along this zone during the Upper Cretaceous period considerable masses of eruptive rock made their exit whereat the calcareous beds became metamorphosed, with the deposition of ore, which occurred partly at the contact itself and partly at points more or less removed therefrom. Three limestone occurrences here enclose most of the deposits, namely those at Vaskö-Dognácska, at Oravicza-Cziklova, and at Szászka-Moldava.

The eruptive rock is of an intermediate type and petrographically to be regarded as coming between the orthoclase and plagioclase rocks. By von Cotta it was named 'banatite.' Previously some portions had been variously described as syenite and syenite-porphyry, and others as quartz-diorite, quartz-trachyte, and andesite. According to

recent investigation by Rozlozsnik and Koloman, these rocks include quartz-diorite, quartz-diorite-porphyrite, granodiorite-aplite, quartzose biotite-amphibole-augite-diorite, gabbro-diorite, quartzose syenite-diorite, and gabbro-diorite-aplite, all these making together a grano-dioritic series. With the plagioclase some orthoclase almost always occurs. The comparative richness of these rocks in iron is worthy of remark, especially as this richness probably stands in causative connection with the iron deposits. These rocks also always contain titanite, though ilmenite is practically absent.

Hungarian geologists agree that the facts available point to the conclusion that the above-mentioned eruptive rocks belong to the end of the Cretaceous period. With their intrusion an eruptive cycle began in Hungary in the course of which during almost the whole of the Tertiary period, andesite, dacite, rhyolite, and basalt, were forced to the surface. Where the eruptives broke through the Tithonian limestone they altered that rock to marble. With increasing distance from the eruptive this alteration became less and less pronounced till finally the limestone remained unaltered. In this unaltered limestone, not far from the contact with the eruptive, Halaváts found nerines and corals from the presence of which he was able to rectify the wrong conception as to the age of this limestone which had previously been held.

The ore occurring in the contact aureole and consisting chiefly of magnetite with some specularite, is accompanied by the usual contact minerals, such for instance as garnet, wollastonite, vesuvianite, mica, tremolite, actinolite, augite, epidote, quartz, etc., and less often by fluorite, richterite, ludwigite, and others. The ore of Vaskö on an average contains some 55 per cent of iron, 0·5–1·75 MnO, 0·10–0·20 P_2O_5, 0·05–0·2 S; often also some copper, but no titanic acid. In the southern portion of this extent of eruptive rock, sulphides of copper, lead, and zinc occur which occasionally carry some gold, while in addition the presence of orpiment and realgar is noteworthy. The ore-bodies, which are generally in the form of chambers or masses, often attain considerable width which in places may reach to 80 m. and more, besides which, veins of pure magnetite are occasionally seen to extend right into the surrounding limestone. They are illustrated in Fig. 48. The genesis of these deposits was in the main properly understood by von Cotta as far back as the 'sixties. In 1885–1886 however his conclusions were questioned by Hj. Sjögren who regarded the ores as sediments and the limestones as members of the Archæan formation.

The most important mining towns of this district are Bogsan, Vaskö or Moravicza, Dognácska, Oravicza, Szaszka, Cziklova, and Uj-Moldava or Neu-Moldava, these places being distributed in a north-south direction between

the river Temes and the Danube. The mining industry thus centred is

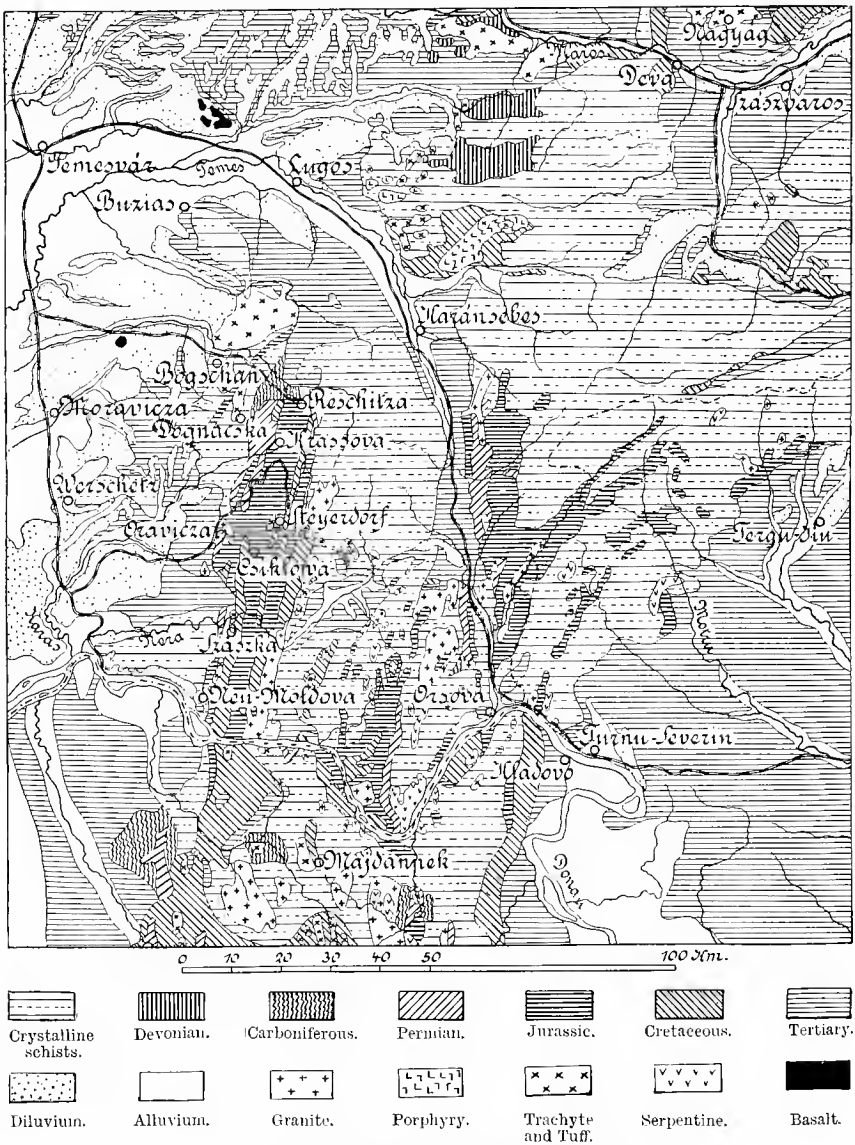

FIG. 230.—Geological map of the Banat contact-deposits, taken from the geological map of Hungary.

an ancient one having been begun in the time of the Romans; Tacitus even, in his time, described the mines of Neu-Moldava. While however

operations formerly were directed chiefly to the winning of the sulphide ores, especially the copper ores of Dognácska, Oravicza, and Szaszka, the lead ores of Dognácska, and the cupriferous and plumbiferous pyrite masses of Moldava, operations to-day are almost confined to the winning of iron ore in the northern portion of the district where near Vaskö the deposits of such ore are of some importance. From 13,000 tons in the year 1857 and 18,000 in 1865, the yearly output from these deposits has risen to 120,000–150,000 tons at the present, to which must be added approximately 1000 tons of pyrite concentrate. In addition, a mineralogically very interesting occurrence of orpiment and realgar, accompanied by fluorspar, is exploited at Neu-Moldava.

Ed. von Suess pointed out that the Krassó-Szörényer fracture zone extends southwards across the Danube into Servia and northwards beyond the river Maros west of the Siebenbürgen mining district. Along both of these extensions it is associated with similar occurrences of ore, among which Rézbánya in the Bihar county immediately at the Siebenbürgen frontier, is the best known.[1] Probably the copper deposit of Maidanpek in Servia, formerly worked by the Romans, belongs also to the group of contact-deposits now being described. Von Cotta in 1864[2] called attention to the analogy of these occurrences with those of the Banat. Pyrite, some chalcopyrite, galena, sphalerite, and magnetite, with generally less than 1·0 per cent of copper, occur in irregular masses or bunches at the contact between andesitic rock and crystalline schists which farther to the north are covered by Upper Cretaceous limestone. The oxidation and cementation zones with 6–10 per cent of copper were considerably richer.[3]

The younger eruptive rocks, principally andesite, which in Siebenbürgen are associated with gold- and tellurium-gold lodes, are occasionally also accompanied by contact-deposits, as for instance at Offenbanya, illustrated in Fig. 49, and at Remez where diasporite occurs in one place in close connection with marble, as the result of contact-metamorphism. In both these cases young eruptive rocks are found in the immediate vicinity. It is however pertinent to remark that diasporite, consisting almost exclusively of the mineral diaspore, is in general of metasomatic formation.

[1] F. Posepny, 'Genesis of Ore Deposits,' *Trans. Amer. Inst. Min. Eng.* XXX., 1901, pp. 98-101.

[2] *Erzlagerstätten im Banat und Serbien*, 1864.

[3] F. Hoffman, 'Sur Maidanpek,' *Ann des mines*, Belgrade, I., 1892.

Contact-Deposits in the Urals

LITERATURE

For Wyssokaia-Gora, Gora Blagodat, and Mednorudiansk.

G. Rose. Mineralogisch-geognostische Reise nach dem Ural, Altai, und Kaspischen Meere, 1837, Vol. I., p. 302.—P. Iéréméew. 'Les Minérais de fer dans les districts miniers de la chaîne de l'Oural,' Jour. des mines, 1859, II., p. 313.—N. Jakovlev. 'Esquisse géologique de la région métallifère des syénites dans le district de Nizné-Tagilsk,' Bull. Com. Géol. Vol. XXV., No. 122, 1906.—F. Loewinson-Lessing. Mitteilungen aus dem Min. Laboratorium des Polytechnikums in St. Petersburg, 1906, Vol. I., and 1907, Vol. VIII.—H. Müller. Ueber den Magnetberg Gora Blagodat, Berg- u. Hüttenm. Zeitg., 1866, p. 54.—A. Karpinsky. Aperçu des richesses minérales de la Russie d'Europe, 1878.—Johanson. Jernkontorets Annaler, 1894.—S. Czyszkowski. Les Venues métallifères de l'Oural. Paris, 1896.—Th. Tschernischew. Guide des excursions du VIIe congrès géolog. internat. St-Pétersbourg, 1897, Pt. IX.—A. G. Högbom. 'Om de vid syenitbergarter bundna jernmalmerma i Östra Ural,' Geol. Fören. Förh. XX., Stockholm, 1898.—R. Beck. 'Die Exkursion des VII. Internationalen Geologenkongresses nach dem Ural,' Zeit. f. prakt. Geol., 1898, p. 25.

The Archæan core of the Ural mountains following the 30th meridian east of St. Petersberg, is flanked to the east by a contorted complex of very varied eruptive rocks and tuffs of late Palæozoic age, between which, small bands chiefly of Devonian limestone are found, these in places being altered to marble. This eruptive chain is formed of porphyry and porphyrite with syenite and gabbro. Associated with the latter is serpentine, and with this again, chromite, platinum, and gold. In the Middle Urals especially, and here again more particularly in the neighbourhood of the railway which from Perm after climbing the Urals leads southwards over Nischni-Tagilsk to Ekaterinburg, rich and famous deposits of iron and copper occur at the contact of the above-mentioned eruptive rocks with the Palæozoic limestones. Among the numerous deposits of iron ore to be found there, that of Gora Blagodat or Holy Hill near Kuschwa and that of Wyssokaia-Gora or High Hill near Nischni-Tagilsk, are the most famous. These two, the first the property of the Crown and the second that of Prince Démidow, form the centre of the iron-industry in the Urals. As indicated in Fig. 150, immediately to the south-east of Wyssokaia the famous copper mine Mednorudiansk is found, while farther to the north in addition to numerous analogous deposits, are the important occurrences at Katschkanar and near Bogoslowsk, of which the former are worked for iron and the latter for copper.

Tschernischew and other Russian and German authorities regard these deposits as magmatic segregations, a view which for reasons more closely discussed below we cannot endorse. As representative of the most important of these deposits those occurring in the neighbourhood of Nischni-Tagilsk and Kuschwa may be more closely considered.

(*a*) *Wyssokaia-Gora.*—The eruptive rock, to the contact with which

we consider the ore formation is to be ascribed and of which the hill itself is composed, is by its holocrystalline structure and composition a very variable syenite, chiefly augite-syenite, while the bands and patches of

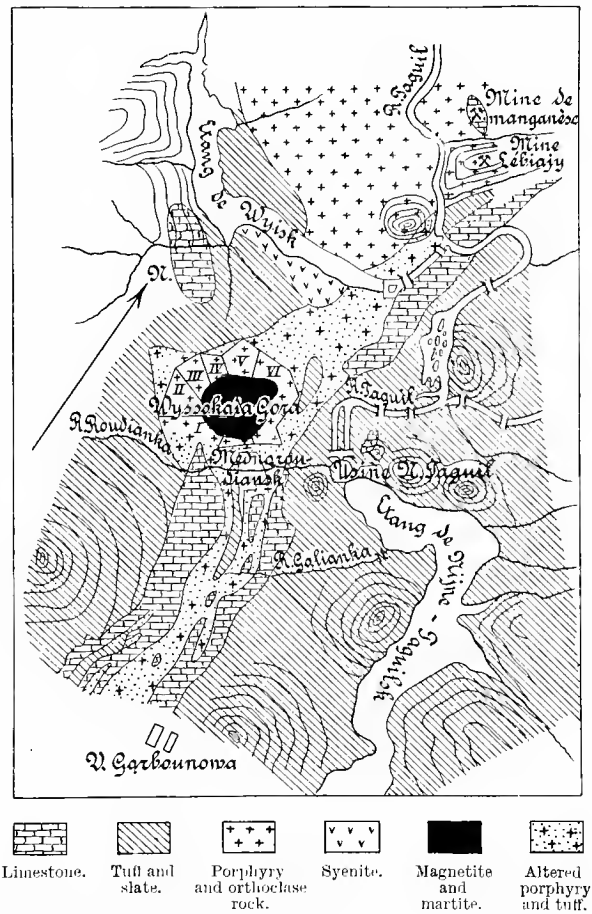

FIG. 231. — Geological map of the Nijné-Taguilsk district including Wyssokaia-Gora, Mednorudiansk, etc., and showing the magnetite mines. Scale, 1 : 112,000. Th. Tschernischew, *Guide des excursions du VIIe Congrès géol. intern. St-Pétersbourg*, 1897, No. IX. p. 8.

I, Nijné-Taguilsky; II, Newiansky; III, Alapaieswky; IV, Werkh-Issetsky; V, Souksounsky; VI, Reodinsky.

compact rock which occur within its mass represent streaked segregations. With this syenite, quartz-free orthoclase-porphyry alternates, which like the syenite consists chiefly of felspar and subordinately of augite and biotite, the felspar being generally represented by microcline and albite. Magnetite also is in places often seen.

The Devonian beds broken by these eruptives consist of alternating limestone, tuff, altered slate, and finally intercalated porphyrite sheets, the black porphyry of the Lyssaia. The limestone, of which there are six horizons and of which the youngest according to Jakowleff contains *Stringocephalus Burtini*, is in greater part altered to a garnet-epidote rock. Högbom believes there is evidence that the porphyry and syenite in places have also been converted into the same rock, in the composition of which according to Loewinson-Lessing, garnet, epidote, chlorite, calcite, and magnetite, take part.

The large magnetite masses of Wyssokaia, though gradual transition from ore to country-rock may occasionally be observed, usually form sharply-bounded and distinctly bed-like masses having sometimes the orthoclase porphyry for country-rock and sometimes the garnet-epidote, while generally speaking they dip to the south-east or to the east. To the south the limestone in which the copper deposit at Mednorudiansk is contained, extends to the occurrence of magnetite. Displacement of the ore-bodies by faulting subsequently to their formation can be observed in more places than one. At their borders the felspathic rocks are kaolinized and occasionally include large blocks of magnetite.

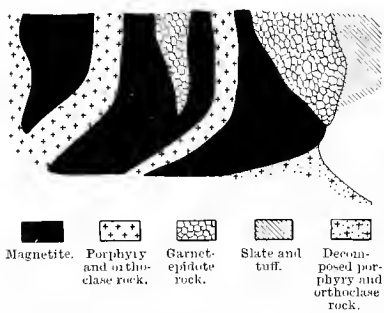

FIG. 232.—Geological map of a portion of Wyssokaia-Gora. Th. Tschernischew.

The garnet-epidote rock is generally regarded as a product of contact-metamorphism. Loewinson-Lessing accepts this genesis also for the ore-deposits, a view which Jakowleff endorses, at least for a portion of the ore. Beck [1] differentiates here both magmatic and contact-metamorphic ores and takes the view that magmatic differentiation and contact-metamorphism proceeded simultaneously.

It is conceded that the genesis of these deposits has not yet been satisfactorily solved, but the fact remains that all those recorded observations of different authorities to which no objection may be taken, may only be explained by contact-metamorphism. The ore is pure containing about 65 per cent of iron, a low percentage of manganese and phosphoric acid, and often sulphur. All these features are characteristic of contact-metamorphic iron ore. The average composition is as follows:

Fe_2O_3 . . .	75·40	Fe, 66 per cent
FeO	16·71	

[1] *Loc. cit.*

Mn_3O_4 . . .	1·30
Cu	0·06
P	0·03
S	Traces
SiO_2 . . .	2·85
Al_2O_3 . . .	1·80
CaO . . .	0·99
MgO . . .	0·98

Mining operations which began at the commencement of the eighteenth century, now keep about twelve blast-furnaces supplied with ore. During the 'nineties about 100,000 tons of iron were produced yearly.

(*b*) *Gora Blagodat.*—Two kilometres from Kuschwa, the centre of the Imperial iron and steel industry, the famous hill of Gora Blagodat rises from its flat surroundings to a height of 1154 feet above the sea and 500 feet above the neighbouring service-reservoir, as an extended elevation facing north-east. This hill consists of different rocks ; to the west and north, of garnet-epidote rock ; on the top and to the east, of orthoclase-porphyry, syenite, and magnetite. The magnetite, that is the ore, disappears as soon as the garnet-rock found in the foot-wall is entered, the two formations mutually excluding one another. On the other hand the ore forms regular, well-defined beds apparently conformable to the orthoclase-porphyry, so that the appearance of regular and conformable alternations of ore and eruptive rock is presented. A remarkable feature is described by Tschernischew who states that almost everywhere the boundaries of the garnet-epidote rock, whether against orthoclase-porphyry, syenite, or ore, follow tectonic planes or faults, so that its normal bedding-relations are nowhere available for observation. This garnet-epidote rock however, it is considered, can only be regarded as a limestone altered by contact-metamorphism. The question whether in the place of the present beds of magnetite some other rock formerly separated the sheets of syenite-porphyry, has so far not been determined or been possible of determination, though the occasional occurrence of small white patches of calcareous material within the ore points to such a possibility.

Evidences of the mechanical action of orogenic forces are not only discernible in the above-mentioned boundary faults but also in the folding which has raised the magnetite beds together with the eruptive masses alternating with them, into an anticline striking north-south, as illustrated in Fig. 234. These same forces also have left their impress in detail in the shearing, kneading, bending, and breaking of crystals, observable in the ore as well as in the eruptive rock. Of the faults two different systems may be distinguished, an older one striking S.S.E. and N.N.W., and a younger one maintaining an east-west direction. Since the fissures of

these faults are filled with breccia and lined with polished surfaces of magnetite these faults are obviously younger than the ore.

While in general the separation of the ore from the red eruptive rock is definite and observable even from a distance, it is occasionally the case that by increase in the amount of felspar present a gradual passage from

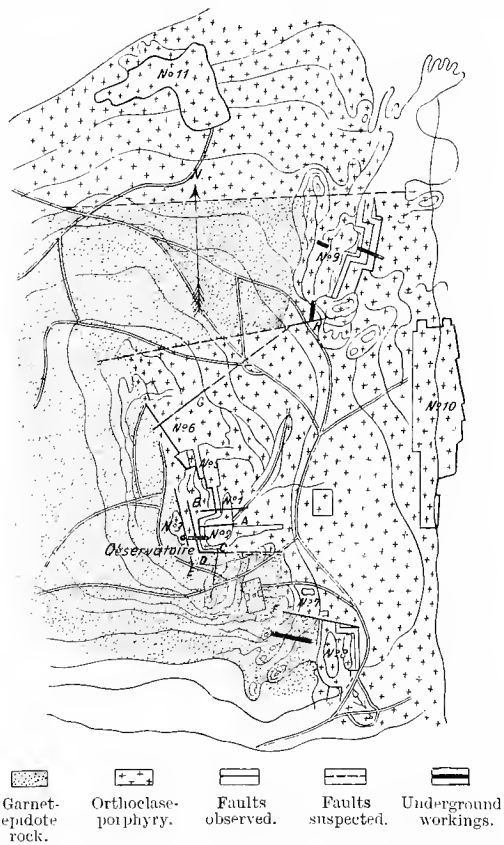

FIG. 233.—Geological map of the Gora Blagodat district. Th. Tschernischew.

ore to a felspathic rock free from ore is presented. This circumstance doubtless suggested the idea of magmatic origin for the ore concerned. Loewinson-Lessing as the result of his investigation came to the conclusion that the ore found intergrown with augite and felspar is younger than those minerals, though it is true he ascribes it to a magnetite magma. Beck on the other hand [1] regarded the loose aggregates and individual crystals of augite and felspar as the early-crystallizing constituents from a magma

[1] *Loc. cit.*

of which the magnetite components, after corroding the earlier crystals, were the last to consolidate. We consider however that the ore which Loewinson-Lessing admitted to be younger has the same genesis as the garnet-epidote rock, and this Beck regarded as a true contact product, a view which is strengthened by the occurrence of garnet crystals in the cavities of the ore. The corrosion of the silicates would be caused by

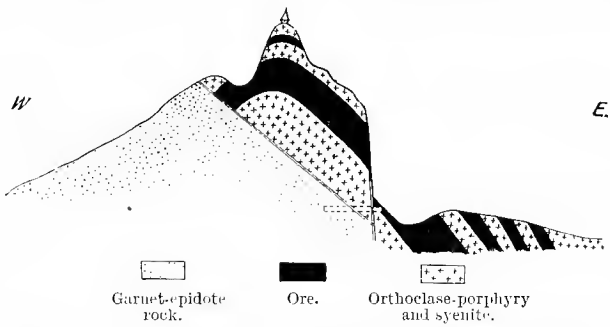

FIG. 234.—Section of the Gora Blagodat deposit. Th. Tschernischew.

the same mineral solutions as those to which the ore, chiefly to be considered as replacing limestone, owes its existence.

The large opencut workings occupy the summit as well as the western slope of the hill. The ore is contaminated by silicates and especially by augite, felspar, and chlorite, so that it contains on an average but 55 per cent of iron, or less than that of Wyssokaia-Gora. Two classes of magnetite are distinguished, a so-called red ore and a blue ore, the latter rendered impure by small scales of chlorite. At the outcrop the ore has been rendered porous and easy to smelt, by the weathering of the chlorite. In depth the blue ore is gradually giving way to red ore. D. J. Mendelejeff gives the following analysis which may be regarded as representative :

Fe_2O_3	52·93	Fe, 53·89 per cent.
FeO	21·65	
Mn_2O_3	0·20	
Al_2O_3	7·18	
SiO_2	9·40	
CaO	6·00	
MgO	1·65	
S	0·05	
SO_3	0·12	
P_2O_5	0·33	
Cu	0·01	
Moisture	0·20	

This ore therefore in regard to the substances present other than iron, is of medium quality. Like almost all contact ore it contains little man-

ganese but some sulphur. The relatively high percentage of phosphorus is however remarkable, since such is not often observed with contact iron ores.

The deposits have been worked since the first half of last century. During the second half they produced 15,000–20,000 tons yearly, while at the present time the production is about 70,000 tons. From 1813 to 1898, 2·75 million tons altogether were won. The resources in 1890 were reckoned at 15 million tons and in 1894 by H. Urbanowitsch at 5 million tons, though they will probably prove to be higher than this latter figure.[1]

The Iron Deposit of Magnitnaia Gora

LITERATURE

J. Morozewicz. 'Le Mont Magnitnaia et ses alentours,' Mém. du Comité Géologique, Vol. XVIII. No. 1; 'Die Eisenerzlagerstätten des Magnetberges im südlichen Ural und ihre Genesis,' Tschermaks min. u. petrogr. Mitt., 1904, XXIII. pp. 113-152 and 225-262; reviewed, Zeit. f. Krist. u. Min., 1906, XLII. p. 489.

The hill Magnitnaia Gora facing the Cossack village Magnitnaia, lies on the left bank of the Ural River and on the eastern slope of the southern Urals; the distance from the town of Mias which is the nearest station on the Ural railway is about 327 km. This mineral district consists of separate hills or short chains, separated by wide valleys. The hill of magnetite 614 m. high is the most important point of an independent chain about 17 km. long and 4 km. wide. It consists of a higher southern portion known as Atatsch, of a northern and principal portion Bezesowaia Gora, of an eastern portion Dalnaia Gora, and of a lower southern portion which includes Malaia Gora and Usianka. In the eastern portion systematic mining is carried on at the Belorezki mines, while in the higher southern portion irregular mining only is done.

The total horizontal extent of the Magnitnaia Gora is about 26 sq. km. It lies in a wide belt of porphyry and felsite which is bounded to the north by granite and syenite, and to the south by porphyrite, diorite, diabase, and tuff. To the west, though still on the hill itself, a small wedge of diabase and diorite penetrates the porphyry and syenite, while to the south and east a width of Lower Carboniferous limestone is similarly found within these rocks. The ore on the one hand occurs in porphyry-syenite and granite, and on the other in diorite and diabase. Garnet, occurring massive as well as in veins or concretions, banded garnet-epidote rock, and iron ore, have been formed by the contact effect of the intruded eruptive rocks.

[1] S. Kusnetzow, 'Die Eisenindustrie des Urals,' *Zeit. f. prakt. Geol.*, 1898, p. 249.

The ore is found over an area about 2 sq. km. in extent and is much mixed with barren rock, which particularly at Dalnaia consists of garnet rock or kaolinized material. It is chiefly magnetite, which mineral occasion-

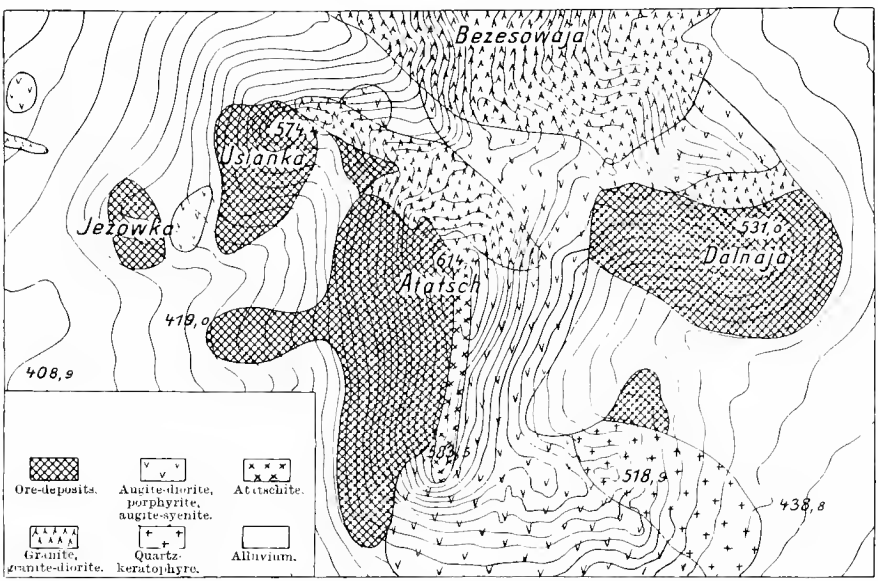

FIG. 235.—Geological sketch of the iron deposits of Magnitnaia-Gora. Scale, 1 : 31,500. Morozewicz.

ally forms large connected masses with surfaces appearing as though they had been fused, though this mineral is often found altered to hæmatite or more particularly to martite. The following figures afford an idea of the general composition of the ore and of its mineral composition.

SiO_2	6·11	per cent.	
Al_2O_3	1·77	,,	
Fe_2O_3	74·74	,,	
FeO	12·04	,,	
MnO	...		
CaO	2·39	,,	
Loss on ignition	2·74	,,	
Total	99·79	per cent.	

Magnetite	36	per cent.	
Martite	48	,,	
Garnet	8	,,	
Kaolin	4	,,	
Quartz	4	,,	
Total	100	per cent.	

Hæmatite and specularite have also been observed intergrown with quartz and garnet, though more rarely they of themselves form large masses of pure ore with a little quartz, alumina, pyrite, and selenite. The following figures illustrate the chemical and mineralogical composition of such ore :

SiO_2	11·06 per cent.	Hæmatite	85 per cent.
Al_2O_3	0·45 ,,	Quartz	10 ,,
Fe_2O_3	82·14 ,,	Pyrite	3 ,,
FeO	0·57 ,,	Kaolin	2 ,,
MnO	0·50 ,,		
Cao	... ,,	Total	100 per cent.
S	0·93 ,,		
Loss on ignition	4·35 ,,	or, Hæmatite	67 ,,
		Quartz	20 ,,
		Kaolin	13 ,,
Total	100·00 per cent.	Total	100·00 per cent.

Botryoidal ore is the name given to the black veins of stalactitic and reniform structure found in weathered argillaceous and granitic rock.

Fig. 236.—Horizontal projection through the Dalnaia mine. Scale, 1 : 1700.
Tscherm. Min. u. Pet. Mitt. Vol. XXIII., plate 4.

It consists of limonite, pyrolusite, and clayey material, and possesses the following chemical and mineralogical composition :

SiO_2	3·91 per cent.		
Al_2O_3	5·85 ,,	Limonite	80 per cent
Fe_2O_3	74·75 ,,	Pyrolusite	10 ,,
Mn_2O_3	7·71 ,,	Clay material	10 ,,
Loss on ignition	8·47 ,,		
Total	100·69 per cent.	Total	100 per cent.

Concerning the manganese it is probable that the high content of this element in the botryoidal ore is due to the secondary enrichment of the very small amount occurring in the bulk of the original ore. These deposits have for a long time been regarded as of contact-metamorphic origin. Morozewicz, in his exhaustive treatise, assumed hydro-chemical processes resulting in the separation and subsequent collection of large amounts of free iron oxide together with garnet and epidote.

The Iron Deposits of Elba

LITERATURE

G. von Rath. 'Geognostisch-mineralogische Fragmente aus Italien,' Zeit. d. D. Geol. Ges., 1866, 1868, 1870, 1873.—J. Cocchi. 'Descr. geol. dell' Isola d' Elba,' Mem. Comit. Geol. d' Ital. I., 1871.—B. Lotti. 'Impressioni geol. di una breva gita all' isola d' Elba,' Boll. geol. Vol. VII., 1876; 'Sui depositi ferriferi dell' Elba,' Rass. Min. Vol. XIV., 1901. —St. Czyszkowski. Régions ferrifères de l'Ile d'Elba. Alais, 1882.—E. Reyer. Aus Toskana. Vienna, 1884.—B. Lotti. Descrizione geologica dell' Isola d' Elba. Memorie descrittive della carta geologica d' Italia, II., 2, 1886; German résumé, Geol. Fören. Förh. XIII., 1891; Zeit. f. prakt. Geol., 1895; also, 'I Giacimenti ferriferi del Banato e quelli dell' Elba,' Boll. Com. Geol. d' Ital., 1887.—L. de Launay. 'Le metallogénie de l'Italie,' Geolog. Kongress zu Mexico, 1906.—A. Fabri. Relazione sulle miniere di ferro dell' Isola d' Elba. Carta geol. d' Ital. III., 1887.—K. Dalmer. 'Die geologischen Verhältnisse der Insel Elba,' Zeit. f. Naturw. 57, 1884; Neues Jahrb. f. Min., 1887, II.; 1894, 1.—Further. a number of papers by L. Bucca, B. Lotti, and S. de Stefani in Boll. Soc. Geol. d' Ital. in the 'nineties.

The island of Elba, not quite 30 km. long, has an extremely varied geological construction. Pre-Silurian, Silurian, Permian, Infra-Lias, Lias, Eocene, and Quaternary beds, are all represented. These are intruded by eruptive rocks represented by granite, quartz-porphyry, eurite, gabbro, diabase, and different serpentinous rocks. The general disposition of these sediments and eruptives is illustrated in Fig. 148.

The age of the granite and the other eruptive rocks was formerly the subject of much discussion. K. Dalmer and B. Lotti, as far back as the 'eighties, concluded that these rocks belonged to the Tertiary period, but this view was later questioned by others. C. de Stefani for instance regarded the granite of Monte Capanne as pre-Tertiary, but the porphyry as Tertiary, while C. Bucca considered that the whole complex must be pre-Tertiary. This question must now be considered as having been finally settled by the investigations of Lotti, which have provided indisputable evidence of the Tertiary age of the granite and of the porphyry and gabbro connected with it. More exactly the age is post-Eocene. In constructing the following description of these occurrences considerable use has been made of the work of Lotti.

The largest of the iron deposits of Elba are found on the east coast of that island, roughly along a north and south line 15 km. in length, which

approximately coincides with the trend of the hills. The ore consists chiefly of iron oxides, specularite, magnetite, and limonite; and subordinately of sulphide ores such as pyrite, chalcopyrite, galena, and sphalerite. These sulphide ores are probably of the same origin as the sulphide contact-metamorphic occurrences at Massa Marittima, Boccheggiano, etc., on the mainland opposite, upon which probability the argentiferous galena of Rosseto described by Lotti has considerable bearing.[1] The iron ore is invariably accompanied by much massive pyroxene, ilvaite, epidote, and garnet. The frequent occurrence of lievrite, or ilvaite as it is called after the island of Elba, a hydrous calcium-iron silicate, otherwise so rare, is remarkable.

The deposits are found at different geological horizons, in most cases

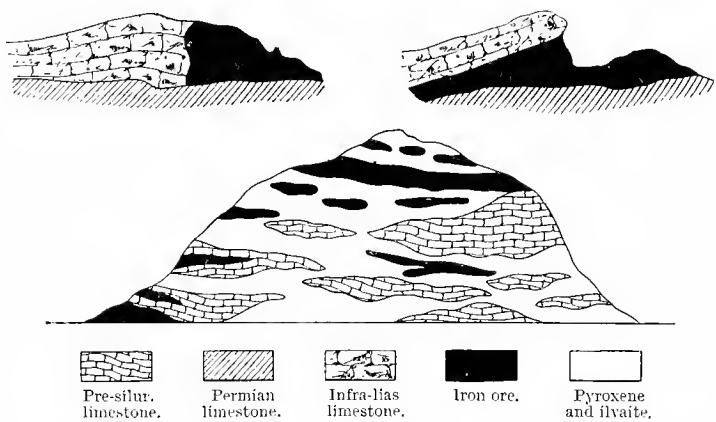

Fig. 237.—Sections through the Elba deposits. Lotti.

obviously replacing limestone. Those of Calamita, Calaginevra, etc., lie between mica-schist and finely-crystalline limestone of pre-Silurian age; at Rio the pyroxene-ilvaite material is found in beds of similar age, while the ore occurs between schistose sandstone and conglomerate of the Permian formation, in part filling hollows in the surface and in part ramifying through a breccia of Infra-Lias limestone. The deposits at Rio-Albano, Vigneria, and Calendozio, occur partly in Permian and Rhaetic beds and partly within argillaceous limestone of the Upper Lias, though they also are found to some extent in the Eocene. Near Terranera the deposit fills a depression in Silurian slates alternating with thicknesses of calcareous material; while finally, that at Capobianco lies upon mica-schist.

[1] K. Ermisch, 'Die Untersuchungen B. Lottis auf Elba,' *Zeit. f. prakt. Geol.*, 1905, p. 141; 'Die gangförmigen Erzlagerstätten der Gegend von Massa Marittima in Toskana auf Grund der Lottischen Untersuchungen,' *Zeit. f. prakt. Geol.*, 1905, p. 206.

Although the ore is generally wont to occur more especially in association with limestone it also occurs in the slaty rocks in the foot-wall. The ore-bodies are occasionally stratified and have the same strike and dip as the limestone with which they are associated. The pyroxene-ilvaite rock sometimes also exhibits this same stratification, and the beds in which it occurs may often be observed to pass over into the limestone or calcareous sediments from which they have been formed. In the deposit at Calamita numerous fragments of limestone may be seen scattered through the pyroxene-ilvaite mass, yet preserving, both in their internal structure and in their outward arrangement, a stratification parallel to that of the neighbouring limestone, indicating plainly that the pyroxene-ilvaite rock had replaced a limestone bed of which the above-mentioned fragments were the remains. Such a replacement is illustrated in Figs. 148 and 237. Lode-like deposits crossing the country are nowhere to be observed.

Upon the island of Elba itself no connection between the ore-deposits and the Tertiary granite can be definitely established, though at Calaginevra and Terranera granitic dykes in the neighbourhood of the ore-bodies are traversed by veins of pyroxene and magnetite. On the other hand, in the case of some of the deposits embraced within a wider circle such a connection is very striking. The ore for example on the neighbouring island of Giglio and at Gavorrano in Tuscany lies at the contact between granite and different sedimentaries, while at Campiglia, on the mainland of Tuscany, there are several other deposits which, possessing the most striking resemblance to those of Elba, are found in close association with granite, quartz-porphyry, trachyte, and masses of pyroxene, ilvaite, and epidote. Of the several analogous deposits in the Tuscan coastal district, those around Massa Marittima have been most completely investigated. In the case of these deposits the iron ore, accompanied by the usual silicates, pyroxene, epidote, and garnet, occurs with Rhaetic limestone in the foot-wall and marl in the hanging-wall. Associated with these occurrences are others of metasomatic origin containing copper- and iron ore, such as are now being exploited at Massa Marittima and Boccheggiano.

The deposits of Elba exhibit very variable composition. They consist chiefly of specularite, subordinately of hæmatite and limonite, and to a small extent of magnetite. In places the lime silicates are absent, as for instance at Rio Albano where however they occur by themselves at Torre de Rio in pre-Silurian limestone. At Calamita the three iron ores mentioned all occur intergrown with garnet, pyroxene, lievrite, and opal, while the presence at Capobianco of limonite containing up to 6 per cent of manganese is worthy of remark, more especially since contact-metamorphic iron ores are usually either entirely without manganese or contain but little of it.

Just as with the occurrences in the Banat, very different views are held relative to the genesis of the deposits of Tuscany, and particularly those of Elba. Some authorities and in particular G. von Rath in 1870, J. Cocchi in 1871, and E. Reyer in 1884, from the bedded character and apparent stratification of the ore and the presence of the pyroxene-ilvaite rock, drew the conclusion that the deposits were actually sedimentary. Their epigenetic nature was however already suspected by different Italian geologists as far back as the middle of last century, since when it has been indisputably established by S. Czyszkowski and B. Lotti, more especially by the latter, who in 1887, in a paper especially devoted to the subject, pointed out the analogy between the deposits of Elba and those of the Banat, and called particular attention to the fact that the deposits of Elba and of the neighbouring mainland were everywhere independent of the age of the country-rock in which they were found. The ore could neither be contemporaneous with the sediments of the hanging-wall nor with those of the foot-wall because in places it equally replaced both, although the geological ages of the two might be quite different.

Since ore is even found replacing beds of Eocene age, these deposits must be regarded as post-Eocene. Together with the accompanying silicates they must have been formed by molecular replacement of the limestone by contact-metasomatis, a procedure which at Calamita is plainly observable to have taken place.

The Etruscans and later the Romans, away back in classic times, sought and won iron ore on Elba. From that time mining operations continued unbroken through the Middle Ages to the present time, though only since the middle of last century have they attained any great importance. Reliable figures concerning the operations since the eleventh century are available. At present the deposits are the property of the Italian Crown. The production in the 'forties amounted to about 30,000 tons per year, rising in 1850 to 50,000 tons and in 1860 to over 70,000 tons. In the 'seventies and 'eighties a maximum of more than 200,000 tons was reached. The present resources are not very great. Since 1831 about 7 million tons have been obtained from Elba, while the quantity reckoned in 1885 as still to be won was placed at 8 million tons.

The iron content of the different deposits varies from 50 to 68 per cent; the manganese content is low with the exception of the ore at Capobianco which contains 6 per cent; there are but traces of phosphorus, though often some sulphur and copper.

Traversella and Brosso in Piedmont

LITERATURE

V. S. A. Bonacossa. Monogr. sulle miniere di Brosso. Turin, 1900.—V. Novarese. Boll. del R. Com. geol. Rome, 1901; Zeit. f. prakt. Geol., 1902.

These deposits, famous for their beautifully formed crystals of garnet, pyroxene, hornblende, epidote, etc., occur in mica-schist and limestone, within the contact aureole of a diorite intrusion. This rock, a biotite-amphibole-diorite, with at most 60 per cent of SiO_2, occupies an area 6 km. long and 2 km. wide, while the actual intrusion is fairly well established to have taken place during the Tertiary period.

Three classes of deposit are differentiated: firstly, magnetite deposits which for years now have not been worked; secondly, deposits of specularite and of pyrite, the latter yielding about 25,000 tons of non-cupriferous pyrite with 48–49 per cent of sulphur yearly; and, thirdly, lodes of lesser importance. With the first two classes the ore occurs in pockets and masses, particularly in the limestone, and the deposits are regarded by the authorities who have recently investigated the district as of contact-metamorphic origin.

The deposits of iron ore near Villa-de-Frades, in the Beja district of the Portuguese province of Alemtejo, where the original magnetite has been changed to martite, the pseudomorph after magnetite, are contact occurrences in the neighbourhood of 'greenstone.' They constitute therefore one of those infrequent cases where within their contact aureole [1] basic eruptive rocks have given rise to a useful ore-deposit.

Contact-Deposits of the United States

It is only within the last few years that the attention of American geologists has been attracted to the formation of ore by contact-metamorphic processes. Among the deposits of iron ore in the United States which belong to this class, those in the Iron Springs district of southernmost Utah deserve special mention. As described by C. K. Leith and E. C. Harder,[2] in these deposits the ore, accompanied by the usual contact minerals often in considerable amount, occurs in the contact aureole of andesite intrusions in Carboniferous Limestone, Jurassic, and Cretaceous beds. This situation is illustrated in Fig. 238 where the Carboniferous Limestone is indicated under the name of Homestake Limestone.

The same authorities state that genetically similar occurrences of

[1] Wernicke, *Zeit. f. prakt. Geol.*, 1902.
[2] *U.S. Geol. Surv.*, 1908, Bull. 338.

magnetite in eruptive rock, or in limestone close thereto, are found in many places in western North America, the United States as well as Mexico. Among others the following places are mentioned: Durango in Mexico, where almost all the iron ore is of this character; San Bernardino County, California; Redding Quadrangle, Northern California; Lyon County, Nevada; the Great Basin; Stevens County, Northern Washington; Texas;

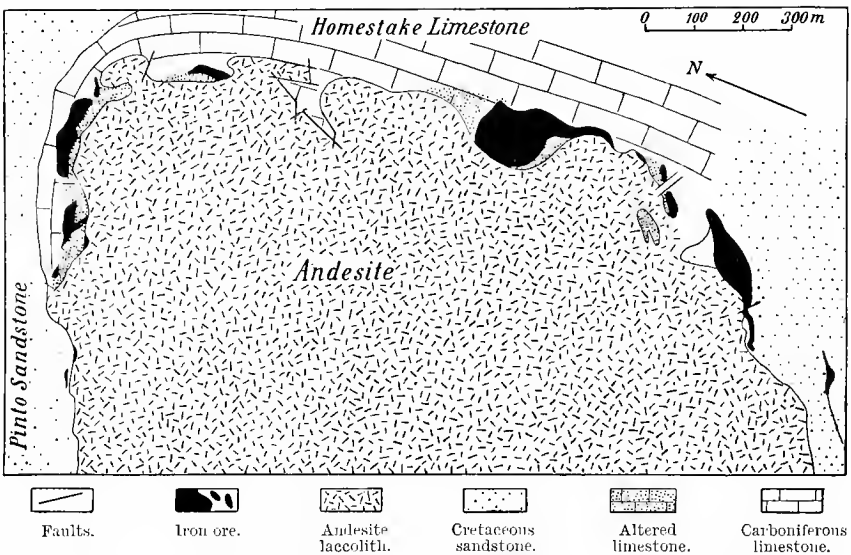

FIG. 238.—Map of the iron deposits at Granite Mountain, Iron-Springs district. Leith and Harder.

Vancouver and Kamloops, British Columbia; Fierro and Chapadera Mesa, New Mexico; Taylor Peak, White Pine and Cebolla district in Pitkin and Gunnison Counties, Colorado; and finally at Iron Mountain, Missouri.

Leith and Harder, on p. 92 of their work, cite many references to these occurrences, and state definitely that the above list of districts where contact-deposits of iron ore are known, is not complete. For further information concerning the contact-deposits of North America, reference should be made to the previously cited papers of Lindgren, Weed, and Barrell.

ANNEX

The occurrences of iron ore in the crystalline schists of Arendal in Norway; and Persberg, Dannemora, etc., in Middle Sweden.

Arendal in Norway

LITERATURE

Th. Kjerulf and T. Dahll. 'Die Eisenerzvorkommnisse bei Arendal, Näs und Kragerö,' Nyt. Mag. f. Naturv. XI., 1861; in German, Neues Jahrb. f. Min. Geol. Pal., 1862.—J. H. L. Vogt. 'Norges Jernmalmforekomster,' with résumé in German, Nor. geol. Unters., 1910, No. 51.

The fundamental rocks of Arendal on the south-east coast of Norway

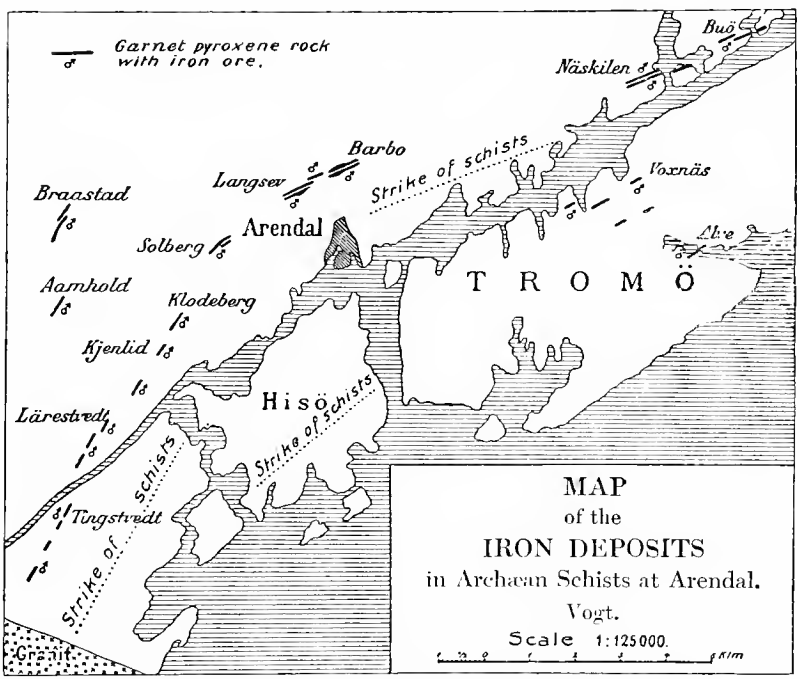

Fig. 239.—Map of the iron deposits in Archæan schists at Arendal. Scale, 1 : 125,000. Vogt.

consist of a number of crystalline members of very variable composition. Red foliated granite rich in potassium felspar, and schistose hornblende-plagioclase gabbro-rocks probably to be regarded as foliated gabbros, are

widely distributed, while, in addition, grey gneiss and hornblende gneiss, both most probably of eruptive origin, are of frequent occurrence.

In such country and within a field approximately 20 km. long, a considerable number of magnetite deposits occur, the positions of which are indicated in Fig. 239. In these the magnetite is associated with augite, generally a diopside variety; garnet, generally andradite; hornblende, epidote, and calcite; to a lesser extent with scapolite, mica, chlorite, serpentine, and spinel; more rarely with babingtonite, rhodonite, tourmaline, datolite, and zeolite, etc.; and now and then with quartz and felspar.

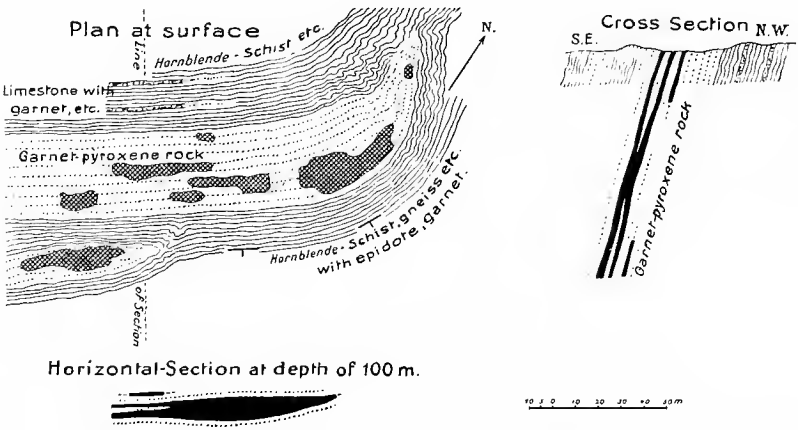

FIG. 240.—The Klodeberg mine near Arendal. Opencut workings indicated by cross-hatching. Vogt.

Often, too, in the neighbourhood of the mines, streaks of calcite with garnet, pyroxene, etc., up to several feet in thickness are found.

These deposits, in their broad lines at least, occur conformably to the crystalline schists and in the manner illustrated in Fig. 240, where lenses of magnetite are seen to occur within larger lenses of the pyroxene-garnet rock. The length of the ore-bodies is rarely more than 75–100 m. The width, which at times, as in the deeper levels of the Klodeberg mine, may be as much as 12–13 m., is generally but 2–5 m. The dip as a rule is steep, while the extension in depth is generally greater than that along the strike. Finally, the composition of the ore may be gathered from the analyses in the following table:

[TABLE

	Klodeberg.	Klodeberg.	Kjenli.	Braastad.	Langsev.
Fe_3O_4	66·06	65·60	59·94	83·98	60·79
SiO_2	10·88	12·00	9·75	7·10	23·28
Al_2O_3	2·75	1·30	1·71	2·83	2·76
MnO	1·87	2·64	2·68	0·20	0·78
CaO	8·38	10·95	12·89	5·00	10·93
MgO	5·38	5·35	7·64	1·15	4·08
P_2O_5	0·018	0·049	0·082	0·066	...
S	0·020	...	...	0·016	...
CO_2	2·69	...	3·40	...	0·30
Total	98·05	...	98·00	100·46	102·92
Fe	47·83	47·5	43·40	60·80	44·02
P	0·008	0·021	0·036	0·029	...

As will be observed, the ore generally contains 42–49 per cent of iron, a percentage as high as 60 being seldom reached. Phosphorus and alumina are low, being generally 0·020–0·035 per cent. There is always more CaO than MgO, while the alkalies are practically absent, as is also titanic acid. The crystals of epidote, garnet, and augite, from Arendal, so often seen in mineral collections, come from these deposits, though those of orthite, euxenite, gadolinite, etc., on the other hand, are from the granite-pegmatite dykes in this same neighbourhood.

Kjerulf and Dahll in 1861 considered these iron deposits, and indeed the Norwegian deposits in general, to be of eruptive origin. According to recent investigation by Vogt however the following factors particularly come into consideration. The iron ore and the garnet-pyroxene rock, locally known as *Skarn*, occur in various crystalline rocks, sometimes in gneiss or hornblende-gneiss, sometimes in the schistose gabbro before mentioned, and sometimes even in the foliated granite. The formation of the ore and of the skarn minerals is therefore younger than the rocks in which they are found, though older than the dykes of granite-pegmatite. The ore and skarn are often striped in conformity with the structure of the country-rock. Sometimes, as for instance in the Torbjörnsbo mine, a typical breccia is met wherein fragments of skarn are cemented by magnetite. The formation of the minerals allied with the magnetite on one side and those with the garnet-pyroxene on the other, took place in this instance in successive stages. The ore and skarn are therefore certainly epigenetic. Within the deposits some layers consist preponderatingly of magnetite; others almost exclusively of kolophonite or garnet, of kokkolite a variety of augite, or preponderatingly of calcite; while others again contain a more equal admixture of these different minerals. In the process of formation ferrous oxide; some manganese oxide, alumina, and carbonic acid; much lime and magnesia; and very much silica, etc., have been added, but

hardly any alkali. This chemical composition and the frequently observed deposition of the chief minerals in separate layers, led to the assumption that the formation depended upon hydro-chemical processes. Since however the mineral association and the structure of the ore and skarn are identical with those of contact-metamorphism, it is justifiable to draw the conclusion that the deposits are either contact-metamorphic pure and simple, or that they are older deposits which have suffered contact-metamorphism subsequent to their original formation which in no case could have been sedimentary. Against this latter alternative there is however the fact that except in the immediate neighbourhood of the deposit the country-rock is not altered by contact-metamorphism. On the other hand the occurrence of the deposits invariably in the near neighbourhood of the granite, often, as at Näskilen and Braastad, actually between foliated granite and crystalline schists, when taken in conjunction with the interbedded occurrence of the former rock, is a further point in favour of an origin by contact-metamorphism.

From about the year 1620 to the late 'seventies the mines at Arendal altogether had produced approximately 2–3 million tons of ore. The total superficial extent of all the deposits is some 8000 sq. m., this total being distributed over twenty larger and a great number of smaller occurrences. Latterly but one or two mines have been working and these only on a limited scale. One mine is 235 m. deep, some are 150 m., and many 100 m. The quantity of ore yet remaining for exploitation has been estimated to be certainly 1·25 million tons, probably 2·25 million, and under favourable conditions perhaps even 3 million tons.

Altogether there are on the south-east coast of Norway no less than five genetically different occurrences of iron ore in the fundamental rocks, namely: (1) iron ore and apatite-iron ore in granite, as at Lyngrot and Solberg; (2) the occurrences at Arendal; (3) titanium-free bedded and brecciated lodes in gabbro at Langö near Kragerö; (4) metasomatic hæmatite occurrences in impure limestone in the neighbourhood of Skien; and (5) titaniferous-iron ore in gabbro.

The Magnetite-Specularite Deposits in the Fundamental Rocks of Middle Sweden

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The long-famous iron ore deposits of Middle Sweden, of which the most important indicated in Fig. 241 have been working since about the year 1300, occur with few exceptions in the upper, though according to Swedish opinion not in the uppermost portion of the fundamental rocks. In that upper portion compact gneisses, variously described by Swedish geologists as hälleflinta or hälleflinta-gneiss and granulite or eurite, are widely distributed. Though these rocks have been more or less altered by regional metamorphism so that the original facies is now often difficult to recognize, many Swedish geologists nevertheless are agreed that in greater part they represent Archæan supercrustal formations. Outpourings of quartz-porphyry with their attendant tuffs played also in their time an important part, though all have since become so foliated and altered that by some they may be considered originally to have been ordinary sediments, while others may regard them as altered plutonic rocks of granitic composition. Limestone and dolomite which in places, as at Dannemora, Persberg, Långban, and Sala, form very considerable beds, are often present. In addition, extensive

areas are found where, though the rock occurs more or less foliated, a granitic character may still be unmistakably recognized. Finally, basic eruptive masses occur here and there.

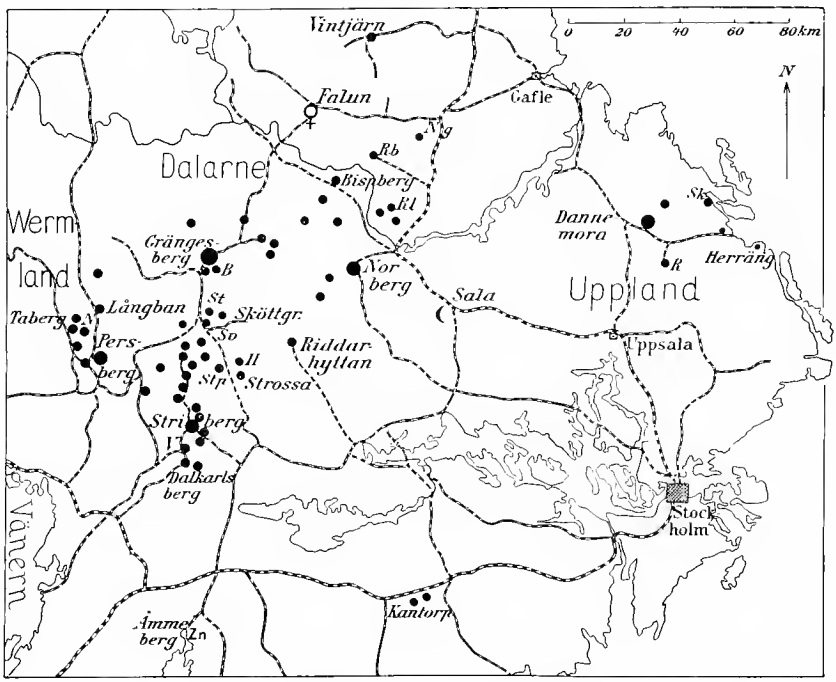

FIG. 241.—Map of the most important iron mines in Middle Sweden. Fahlun is a copper mine; Sala, a lead-silver-zinc mine; Åmmeberg, a sphalerite mine. Nordenström, 1897.

N, Nordmarken; *V*, Viker; *Stp*, Stripa; *Il*, Håkonsboda; *Sv*, Svartvik; *St*, Ställberg; *B*, Björnberget; *Rl*, Ryllshytan; *Rb*, Rallingsberg; *Ng*, Nyäng; *R*, Ramhall; *Sk*, Skedika.

According to the views of some Swedish geologists, the granulites etc., are not to be regarded as having consolidated at the surface but in depth, subsequently to which they were greatly altered.

The ore-deposits are in greater part steeply-inclined, and almost always conformable to the country-rock, while the ore itself is often banded. In the majority of cases this latter is almost exclusively magnetite; in some cases specularite preponderates and magnetite is unimportant; while in others both minerals may be well represented. Limonite and siderite are absent and all the ores here occurring are without titanium. Mineralogically and chemically therefore, as well as in regard to geological position, extreme members of these occurrences may be differentiated, these being represented by Grängesberg on the one side and Dannemora on the

Analyses of Iron Ores of Middle Sweden

		Fe_2O_3	Fe_3O_4	FeO	MnO	SiO_2	Al_2O_3	CaO	MgO	P_2O_5	S	Ignition Loss	Total	Fe	P
Grängesberg, Apatite-Iron Ore	1	73·50	14·81	...	0·04	1·62	0·63	5·09	0·82	3·53	Trace	...	100·04	62·18	1·54
	2	9·13	79·04	...	0·10	2·00	1·78	3·61	2·72	2·42	0·013	...	100·81	63·63	1·06
	3	...	86·54	0·32	0·13	4·82	1·64	3·50	1·69	1·90	0·013	...	100·55	62·92	0·83
Striberg, Lean Ore	4	47·32	26·78	...	0·19	23·80	0·35	0·95	0·40	0·034	0·020	...	99·84	52·52	0·015
	5	45·30	27·62	...	0·13	26·00	0·30	0·50	0·18	0·030	0·014	...	100·07	51·71	0·013
	6	60·60	12·42	...	0·22	24·55	0·29	1·80	0·18	0·005	0·014	...	100·08	51·44	0·002
	7	59·86	10·35	...	0·37	23·50	0·94	2·90	1·44	0·050	0·008	...	99·42	49·40	0·021
Persberg - Dannemora, Skarn-Ore	8	50·92	...	23·00	0·31	9·22	0·65	5·87	5·66	0·030	0·015	3·68	99·36	53·54	0·013
	9	50·13	...	23·55	0·34	8·10	2·03	5·46	7·86	0·025	0·014	3·38	100·89	53·48	0·011
	10	...	74·71	...	0·47	13·71	0·92	5·72	4·83	0·021	0·035	...	100·46	54·10	0·009
	11	...	74·84	...	0·14	14·40	0·40	4·04	6·08	0·019	...	...	99·90	54·40	0·008
	12	...	71·65	0·71	2·23	9·30	1·49	5·20	5·66	0·005	0·027	3·00	99·27	52·40	0·002
	13	44·03	...	23·55	2·55	7·78	1·64	7·74	4·43	0·013	0·011	8·08*	100·69	49·14	0·006
	14	...	64·22	6·17	7·43	8·00	2·17	2·64	3·08	0·021	0·044	4·90	99·78	51·30	0·009
	15	...	58·87	6·39	6·67	5·10	2·20	3·60	5·19	0·007	0·052	12·30	100·29	47·60	0·003
		Fe_2O_3	Mn_3O_4	PbO	BaO	SiO_2	Al_2O_3	CaO	MgO	P_2O_5		CO_2	Total	Mn	P
Långban, Manganese Ore	16	1·44	65·62	0·06	2·81	1·68	...	9·18	5·56	...	...	14·30	100·65	47·28	...
	17	1·54	57·59	1·47	2·36	12·84	Trace	10·90	4·50	0·087	...	7·60	98·69	41·36	0·038

other. The occurrences may accordingly be divided into the following groups :

1. Apatite-iron ore : Grängesberg.
2. *Torrsten* or lean ore : Striberg.
3. (*a*) Ore carrying hornblende, augite, garnet, etc. : Dalkarlsberg, Nordmarken, Taberg in Wermland, Persberg.
   (*b*) Ore carrying the above minerals together with calcite : Dannemora.
4. Manganese ore, chiefly haussmannite : Långban.

Apatite-iron ore and other rich iron ores are found at Grängesberg, the most important mining field in Middle Sweden. In this field, which is about 4 km. long and 0·5 km. wide, the strike of the ore-bodies, as indicated in Fig. 150, is fairly regular and the dip, which is about 65°, equally so. The country-rock in the immediate neighbourhood of the ore consists of grey biotite-granulite with interbedded occurrences of amphibolite, though foliated granite occurs only a hundred or so metres distant from the hanging-wall of the principal deposit.

Fig. 242.—Section of the main bed at Grängesberg. Vogt., *Geol. Fören. Förh.* XVI., 1894, p. 289.

a, Halleflinta-gneiss ; *b*, iron-mica-schist ; *c*, specularite ; *d*, magnetite ; *e*, magnetite with much apatite ; *f*, dyke of granite-pegmatite ; *g*, contact-metamorphic zone along the granite dyke wherein the specularite is altered to magnetite.

The ore-bodies themselves are lenticular masses of very variable width. The length of the largest among them is about 1000 m., along which length there are two bulges where the width is respectively 90 m. and 110 m. Within that width, as indicated in Fig. 242, there are alternating layers of magnetite and specularite, the former predominating, as well as some quartz, hornblende, etc., and a good deal of apatite. The ore is crossed by numerous dykes of granite-pegmatite which for a foot or more on either side have altered the specularite to magnetite. The ore of the main deposit carries on an average 62 per cent of iron and 1 per cent of phosphorus which is equivalent to 5·5 per cent of apatite. At Ormberget and Lomberget the phosphorus content is much lower. The whole occurrence mineralogically, chemically, and geologically, is remarkably similar to that of Gellivare.

The so-called *Torrsten* or lean ore found at Striberg and in several mines at Norberg, consists of an intimate mixture of specularite and to a less extent of magnetite, with quartz and various silicates. That at Striberg greatly resembles the quartz-banded ore of Sydvaranger in Norway, so much so that Fig. 183 might well be taken to represent it ; there is however the important difference that the Swedish ore, containing 50–53 per cent of iron, is materially richer. The amount of sulphur present is low, and

the phosphorus in some mines is but 0·01 per cent. Though this latter figure is in places exceeded it is rarely more than 0·04 per cent. The amount of manganese present is invariably minimal. The deposits of ore of this class are mostly immediately embedded in hälleflinta or hälleflinta-gneiss.

The ore carrying hornblende, augite, garnet, etc., and in some cases much calcite, and the manganese ore, differ geologically from the apatite and lean ores mentioned above in so far that they occur almost invariably in close connection with limestone or to a less extent with dolomite, being found either actually within those rocks or in close proximity to them. That of Dannemora, for instance, as indicated in Fig. 244, actually occurs in limestone as do also those of Klackberg and Kolningberg, near Norberg, illustrated in Fig. 245; that of the principal occurrence at Persberg

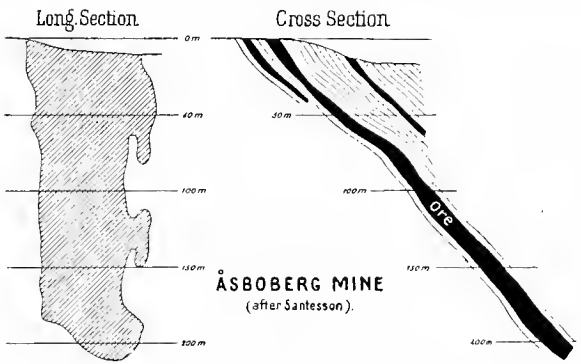

Fig. 243.—Sections of the Åsoberg Mine, after Santesson.

partly, as indicated in Fig. 246; and in addition the Hag, Skött, Högborn, Holm, Viker, Svartvik, Ställberg, and other mines. The situation of the last-named occurrence is indicated in Fig. 247.

It is just these occurrences which are characterized by the large development of skarn, this rock generally consisting of a schistose complex of hornblende, augite, garnet, epidote, chlorite, talc, serpentine, etc., often with calcite and sometimes with quartz. The skarn here, similarly to its occurrence at Arendal in Norway illustrated in Fig. 240, often forms lenses of considerable dimension within which again the lenticular or irregular ore-bodies occur.

The ore of these deposits is chiefly magnetite and but seldom specularite. It occurs mixed with the skarn minerals with which sometimes there is a good deal of calcite in addition. The iron content is usually about 50 per cent; that of manganese is sometimes high, as for instance at

Dannemora where, among other minerals, the ore is mixed with the man-

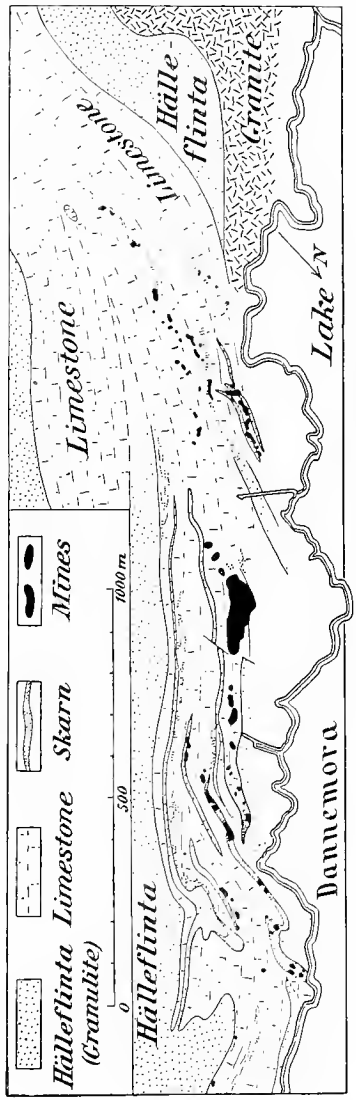

Fig. 244.—Map of Dannemora. Tornebohm.

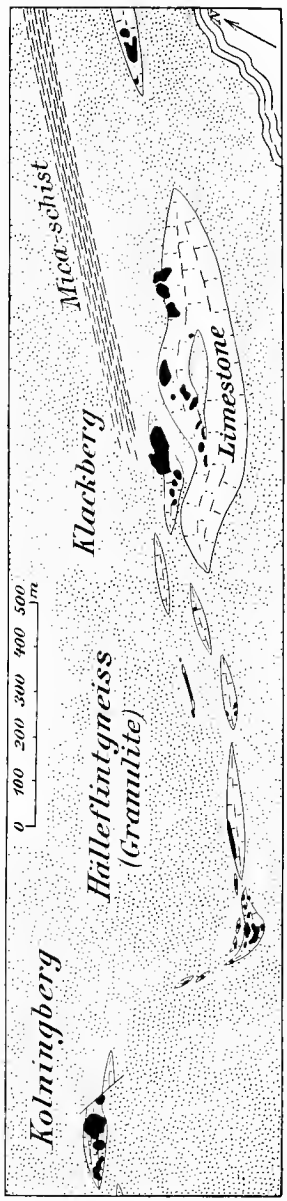

Fig. 245.—Map of Klackberg-Kolningberg. W. Petersson.

ganese-iron olivine, knebelite. The amount of phosphorus is generally very low, at Dannemora only 0·002–0·005 per cent and at other occur-

rences often less than 0·01 per cent. That of sulphur on the other hand is sometimes somewhat high.

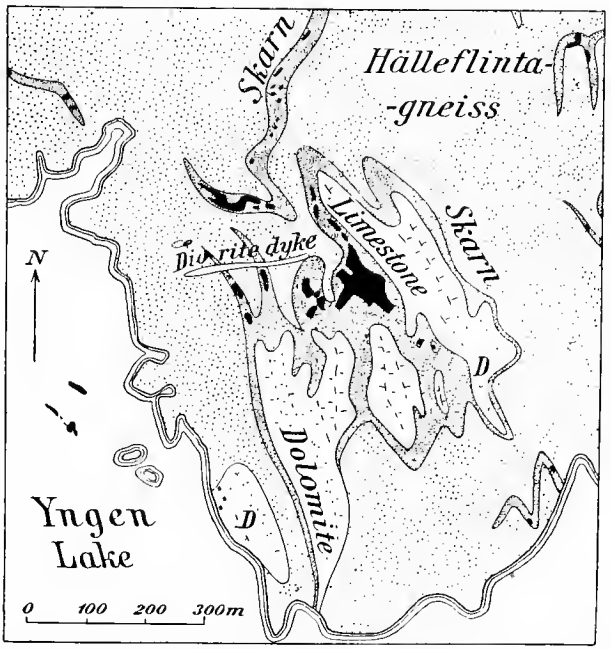

FIG. 246.—Map of the principal portion of the Persberg field ; ore and workings indicated black. Törnebohm.

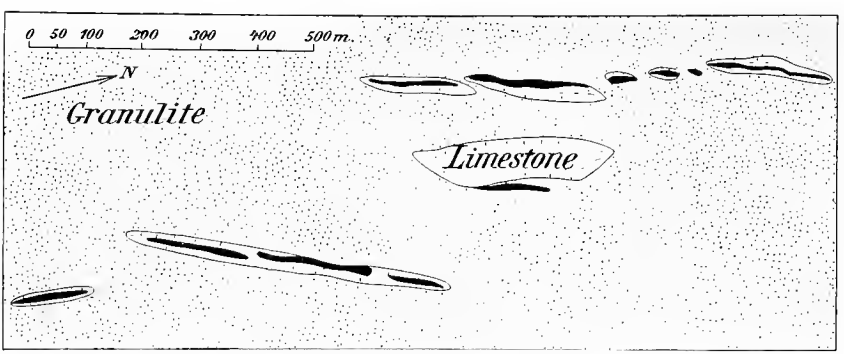

FIG. 247.—Map of the Ställberg field ; showing iron deposits in limestone lenses. Santesson.

Similarly to the Arendal ores, those of Nordmarken, Persberg, Dannemora, etc., are distinguished by the presence of mixed silicates which generally carry a good deal of lime and magnesia though relatively little

alumina. The lime often exceeds the magnesia though at times the opposite is the case. The alkalies are almost completely absent.

The ore-bodies are lenticular, sometimes indeed almost columnar, so that the length along the strike is but a low multiple of the width. The largest body at Dannemora has a length of 240 m. and a maximum width of 30 m. In the majority of cases however the length is less and often below 100 m., while the width is usually not more than 10 m., and often only

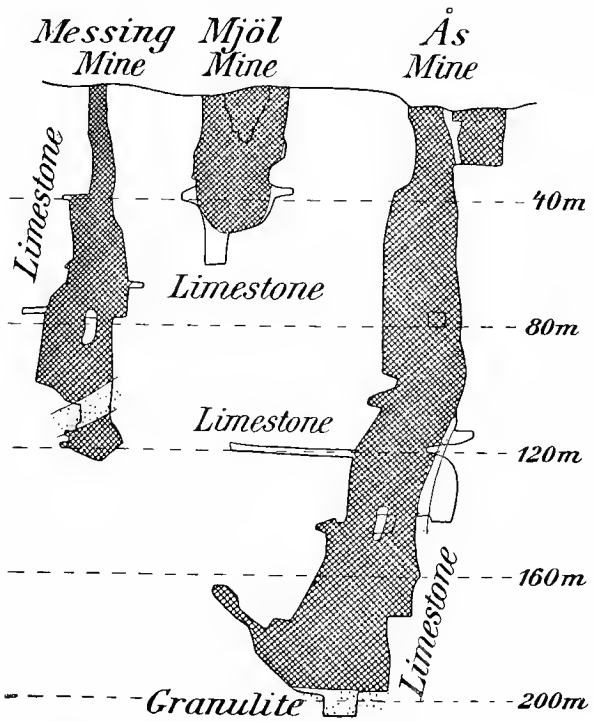

FIG. 248.—Longitudinal section of three ore-bodies in limestone following one after the other along the strike. Svartvik. Santesson.

2–5 m. With some exceptions the extension in depth is generally considerably greater than that along the strike, a dimensional relation illustrated in Figs. 243 and 248. Many mines with a length of 100 m. or less are now working at depths of 200–300 m., while two mines, Taberg in Wermland and Dalkarlsberg, have reached 350 m. with no perceptible diminution in horizontal dimension. On the other hand many deposits, and especially the smaller ones, have given out at comparatively shallow depths. Not infrequently the deposits pitch into the country, that is the extension in depth does not coincide with the dip but makes

an angle with it. Another feature of their occurrence is that they often follow one another at short distances along the strike, as illustrated in Figs. 245 and 247, though this arrangement may be varied by one in parallel steps seen also in Fig. 247. Whether this appearance is primary or due to subsequent folding, is not possible of decision by direct observation.

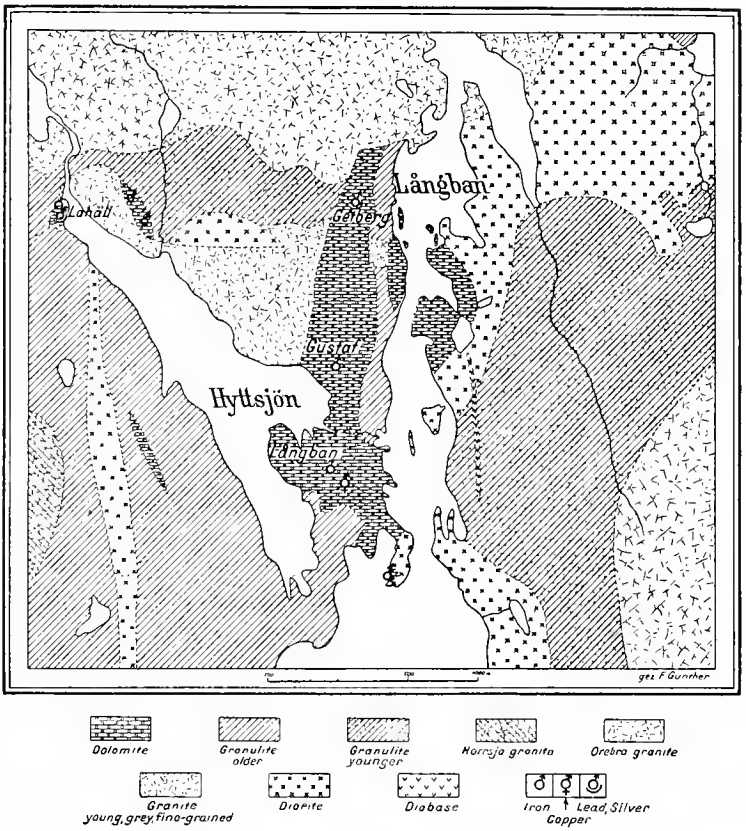

FIG. 249.—Geological map of the Långban district; scale, 1 : 50,000.

The strike is often in good line though occasionally, as illustrated in Figs. 21, 70, 71, and 72, it is curved or even jagged. Irregularity of strike, as illustrated in Fig. 246, also occurs. On either wall, or on both, the ore-bodies often occur with false walls which in general are probably rightly regarded as planes of movement, and therefore of tectonic origin. When exploring underground, such walls, especially if they are wet, are considered favourable indications of the presence of a new ore-body.

The manganese occurrences at Långban in Wermland and at the five

neighbouring places Pajsberg, Harstigen, Jakobsberg near Nordmarken, Kittelen at Nordmarken, and Sjöggrufvan, are peculiar, and mineralogically of the greatest interest. The Långban mine, which occurs within a large area of dolomite, contains specularite in large flat lenses and manganese ore in lenticular or clump-like masses. The production of these two ores

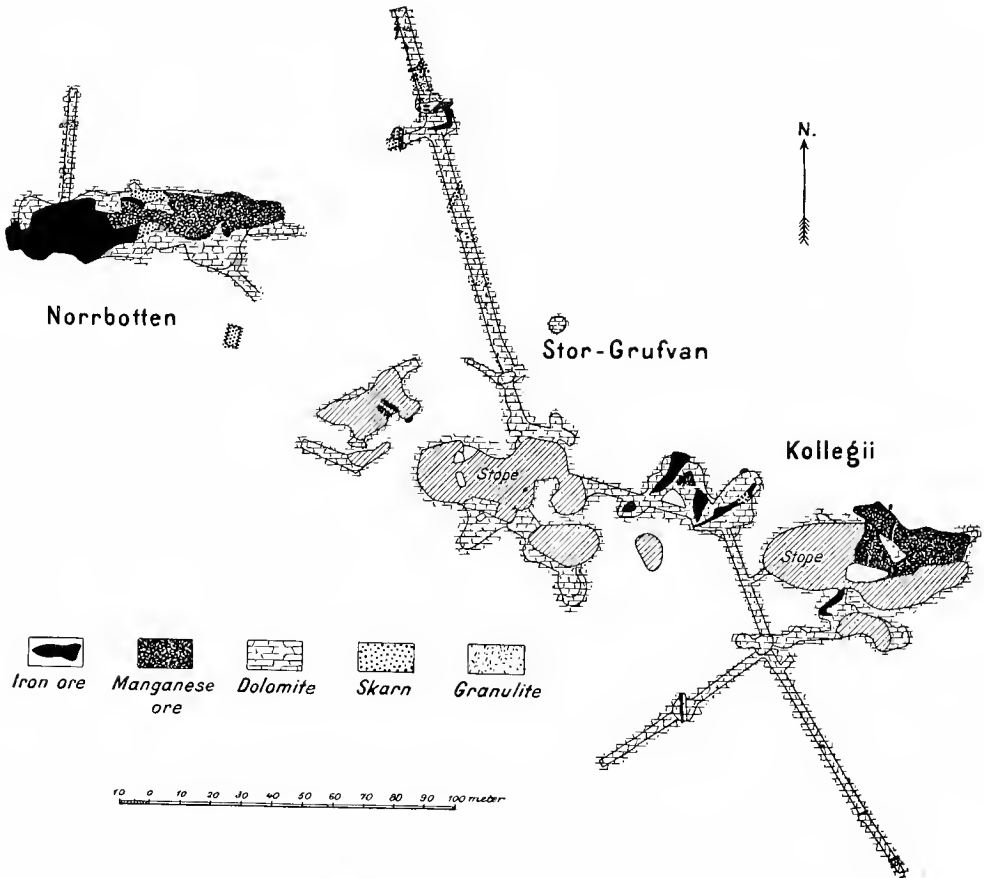

FIG. 250.—Horizontal section of the iron and manganese deposits at Långban.

which are mined separately, has been latterly about 7000 tons of the former with 50–60 per cent of iron and but 1 per cent of manganese, and about 3000 tons of the latter with 30–40 per cent of manganese and but 1 per cent of iron. The occurrence at Kittelen in the Nordmarken mine was that of a clump-like body of manganese ore, of dimensions not exceeding a few metres in any direction, in the immediate neighbourhood of the iron ore. The other four occurrences are only of mineralogical interest.

The manganese deposits of Långban, consisting chiefly of haussmannite with some braunite, as well as that found in the iron mine of Nordmarken, are in regard to the variety of minerals found in them among the most prolific and interesting in the world. According to a collection made at our request a few years ago by Professor A. Hamberg of Upsala, the presence of at least 120 independent minerals has been established, including 48 which so far are limited to these particular deposits. Next after these in the abundance of minerals presented, come the occurrences at Monte Somma, Vesuvius, and those in the district of Langesundfjord in Norway, each with some 80 different minerals.

In the above-mentioned manganese deposits many and various compounds of manganese, lead, barium, arsenic, and antimony, are found, such for instance as manganosite, MnO and periclase MgO ; jacobsite, rhodochrosite, and rhodonite ; schefferite or manganese-augite ; tephroite or manganese-olivine ; manganese-vesuvianite and manganese-epidote ; manganophyllite and trimerite ; pyrophanite, $MnTiO_3$, etc. ; metallic lead ; the five lead silicates, barysilite, ganomalite, hyalotekite, kentrolite, melanotekite ; in addition, celsian or barium felspar ; långbanite, a manganese-iron-antimony silicate ; and numerous arsenates, etc. Nordmarken among other things is famous for its diopside crystals.

The deposits of Middle Sweden just described, present great difficulty in the matter of their genesis, more particularly as in many cases the original nature of the country-rock cannot be determined. The older Swedish geologists and mining engineers, including Erdmann, Gumälius, Nordenström, A. Sjögren, and Törnebohm, regarded the occurrences as sediments, a view endorsed by Hj. Sjögren in 1885, 1886, and 1891, and by Vogt at the commencement and in the middle of the 'nineties, while to-day it has still a number of adherents. The arguments put forward were the conformity with the country-rock, the striping and banding of the ore, and the limitation of certain ores to particular geological horizons.

In 1893 Hj. Sjögren, altering his view, endeavoured to explain these occurrences as the result of metasomatic processes. He and Tiberg, the latter particularly, were of opinion that they were deposits from descending aqueous solutions rich in iron. In view of the fact however that a whole number of these occurrences are crossed by dykes of trap and of granite-pegmatite, the latter certainly of Archæan age, the ore formation must equally be of Archæan age. Of late years Hj. Sjögren has strongly advocated the view of a later and intensive alteration of the deposits and according to him two principal factors have to be considered, the primary origin and the secondary alteration.

The older Swedish school, as well as Johansson and Hj. Sjögren, have latterly sought to explain the whole of these occurrences by one

method of formation applicable, in its chief features at least, to all. The old school in this endeavour assumed original sedimentation, Johannson magmatic differentiation, while the view of Hj. Sjögren may be gathered from the following quotation[1] 'That one manner of formation . . . is . . . magmatic-aqueous fusion which on the one hand may pass over to become ordinary solution and on the other to become magmatic differentiation.'

The formation of such varied occurrences, as for instance those of Grängesberg, Striberg, and Persberg-Dannemora, by one single process, appears however very doubtful. Vogt calls particular attention to the fact that in the fundamental rocks of that district in Norway which includes Arendal, Kragerö, and Ulefos, a district much less extensive than that now being considered, no less than five genetically-different classes of iron deposits occur, among which four are titanium-free (see p. 378). A similarly varied genesis is probably the case with these deposits of Middle Sweden. The apatite-iron ore of Grängesberg shows a remarkable similarity to that of Gellivare and like it probably arose by magmatic differentiation. Then there are other occurrences in Middle Sweden which may be compared with the Solberg-Smorten type of Norway. As pointed out by Vogt [2] and later amplified by Hj. Sjögren, the *Torrsten* or lean ore of the Striberg type, occurring in granulite and orthogneiss, is structurally almost identical with the quartz-banded ore found at Sydvarangar in northern Norway. It is therefore possible that the lean ore of Sweden was also formed by magmatic differentiation. In any case between the apatite-iron ore and the lean ore several intermediate stages are found.

The remaining class of deposit, that typically developed at Persberg and Dannemora and characterized by fluctuating amounts of augite, hornblende, garnet, etc., and sometimes of calcite, must, with the manganese deposits, be considered apart from the others. The occurrence of such deposits of iron and manganese in one and the same mine, at Långban and again at Nordmarken, indicates that the two occurrences must be considered together. These deposits in their form of extended lenses amounting almost to columns, are morphologically widely different from sediments even when such have been mechanically deformed. At Långban the dolomite in the neighbourhood of the mine is traversed by a number of veins of iron as well as of manganese ore running at right angles to the main deposit,[3] proving most convincingly that the ore there is epigenetic.[4] The deposits of the Persberg-Dannemora type are also occasionally crossed by dykes of granite-pegmatite and trap of Archæan age, to which age therefore their formation also must be relegated.

[1] *Geol. Fören. Förh.* XXX., 1908, p. 152.
[2] *Zeit. f. prakt. Geol.*, 1907, p. 88.
[3] See photographs by B. Tiberg, *Wermländska Annalen*, 1903, Pt. II., Plate I.
[4] Vogt, *Zeit. f. prakt. Geol.*, 1900, p. 371.

In relation to the minerals present these occurrences are identical with the contact iron deposits. Hj. Sjögren in the 'eighties drew a parallel between Persberg on the one side and Vaskö, etc., in the Banat on the other, while Törnebohm [1] compared Persberg, etc., with Pitkäranta. In making these comparisons both these authorities proceeded from the idea that the Persberg occurrence was sedimentary, an origin which they then sought to apply to the Banat and to Pitkäranta respectively. Since however the deposits at the two latter places are now acknowledged to be contact-metamorphic or contact-metasomatic deposits, the similarity thus established with that of Persberg strengthens the view that the Persberg-Dannemora deposits are equally of similar genesis. The geological position of these deposits, characterized as it is by association with limestone or dolomite, is strikingly similar to that of deposits freely acknowledged to be contact-metamorphic. The same similarity is seen in the shape of the ore-bodies and in their frequent limitation by movement- or crush-planes. For ages Persberg has been particularly compared with Arendal, the Archæan deposits of which latter place Vogt considers almost certainly to be of contact-metamorphic origin, an origin which by analogy he considers may be applied to the equally Archæan Persberg occurrences. This view of their genesis is however only of an hypothetical character. With the deposits of Middle Sweden there remain so many unsolved questions, one in particular being that of the origin of the country-rock, that the question of the genesis of the ore-deposits themselves must be handled with the greatest caution.

Economics.—The total production of iron ore from Sweden according to H. Sundholm [2] amounts altogether to about 113 million tons distributed as follows over the different periods :

1301–1700	=	400	years	some	11·8	million tons.
1701–1800	=	100	,,	,,	15·7	,, ,,
1801–1832	=	32	,,	,,	5·7	,, ,,
1833–1857	=	25	,,	,,	6·9	,, ,,
1858–1877	=	20	,,	,,	10·5	,, ,,
1878–1897	=	20	,,	,,	22·9	,, ,,
1898–1908	=	11	,,	,,	39·2	,, ,,
Approximate total					113·0	million tons.

From Norrbotten up to the end of 1908, as mentioned on p. 275, about 23·3 million tons were shipped. The export from Grängesberg from 1882 to 1908 amounted to 8·9 million tons ; from other mines in Middle Sweden somewhat more than 1 million tons were latterly shipped to Germany, etc., while since 1809 about 1 million tons have been sent to Finland making altogether in round figures about 33 million tons shipped. In the country

[1] *Geol. Fören. Förh.* XIII., 1891.
[2] *Berghandheringens Vänner*, Örebro, 1909.

itself till the end of 1908, 79–80 million tons had been smelted, of which about 0·9 million tons came from Taberg in Småland while the remainder came from the deposits of Middle Sweden just described, the total production of which to the end of 1908 amounted to about 89–90 million tons.

The Swedish production of iron ore and pig-iron is as follows:

Metric Tons.	Iron Ore.		Pig-Iron.
	Total.	Proportion from Middle Sweden.	
1871	662,500	about 660,000	298,800
1881	826,100	,, 820,000	430,000
1891	987,400	,, 950,000	490,900
1901	2,795,200	,, 1,700,000	528,400
1907	4,480,100	,, 1,831,710	567,800
1908	4,712,500,	,, 1,884,450	556,345

With few exceptions the Swedish blast-furnaces use charcoal only in smelting and produce an iron famous for its low sulphur and phosphorus content.

The tonnages of iron ore produced by the most important mining-fields in 1908 were as follows:

Norrbotten.

	Tons.
Kiirunavaara-Luossavaara . .	1,649,850
Tuollavaara	78,730
Gellivare	869,010
Koskulls Kulle	195,855

Middle Sweden.

	Tons.
Grängesberg, with Lomberg } high P-content	715,210
Blötberg } high P-content	129,840
Idkerberg } high P-content	59,120
Norberg, with eleven separate mines .	145,540
Dannemora, several mines . .	46,240
Strossa ,, ,, . .	44,790
Stripa ,, ,, . .	37,660
Sköttgrufve ,, ,, . .	36,230
Ställberg ,, ,, . .	35,900
Dalkarlsberg ,, ,, . .	33,870
Striberg ,, ,, . .	30,190
Persberg ,, ,, . .	29,730
Herräng ,, ,, . .	26,300

In addition to those above-mentioned, twelve smaller mining fields each produce annually 10,000–20,000 tons, while many still smaller are in operation. Putting all together, the total number of mines working in Middle Sweden during the year 1908 was no less than 277.

Of the total iron ore produced in Sweden the greater part, latterly about three-quarters, is derived from the apatite-iron mines, the remaining

quarter being fairly equally distributed between the lean ore and the skarn ore.

At many of the mines in Middle Sweden the poorer ore, separated by hand from the richer, is afterwards concentrated, this being accomplished almost entirely by wet-magnetic processes. In the year 1908, 23 equipments operating this process were at work by which during that year 585,000 tons were treated, producing 262,620 tons of concentrate, 156,590 tons of which were briquetted. Apart from the apatite-iron ore, the hand-sorted ore generally contains 50–60 per cent of iron, or about 53 per cent on an average, while that won by magnetic separation contains about 60 per cent.

With regard to the depth of these Swedish occurrences, the Ormberg mine near Grängesberg is 470 m. deep ; three mines in Wermland, namely Åsboberg, Dalkarlsberg, and Taberg are approximately 350 m. ; about eight are between 250 m. and 350 m. ; many between 200 m. and 250 m. ; and a very considerable number between 150 m. and 200 m.

With regard to extent, the different fields may be compared by the total horizontal area of the ore-bodies contained in each, a comparison already adopted on p. 274 for the occurrences at Norrbotten. For Middle Sweden, Nordenström in 1899 reckoned the total superficies of the many mines at 298,500 sq. m., in which figure the titaniferous occurrence at Taberg in Småland is not included. The following are some of the individual figures :

	sq. m.
Grängesberg { total	90,000
Grängesberg { principal body	40,000
Norberg, many separate mines	30,000
Dannemora, several mines	12,500
Striberg	7,000
Stripa	6,700
Persberg	4,285
Strossa	3,200
Finmossen	2,900
Sköttgrufve, several mines	2,780
Klacka-Lerberg	2,100
Ställberg	1,580
Svartvik	792
Nordmarken	1,240
Taberg in Wermland	940

F. R. Tegengren [1] divided the resources of Middle Sweden into (*a*) ore with less than 0·01 per cent phosphorus ; (*b*) ore with 0·01–0·06 per cent ; (*c*) ore with more than 0·06 per cent, including the principal body at Grängesberg which has about 1 per cent. He further differentiated between cobble ore, raw ore, and concentrate, as in the following table :

[1] *The Iron-Ore Deposits of the World*, Stockholm, 1910.

Iron Ore of Middle and Southern Sweden

Phosphorus Content.	Cobble Ore.	Raw Ore.	Concentrate therefrom.	Cobble Ore + Concentrate.
Under 0·01 per cent . . .	19·4	45·5	28·0	47·4
0·01–0·06 per cent . . .	11·5	6·1	2·9	14·4
0·06 per cent and above . .	59·3	2·0	1·2	60·5
Totals, in million tons . .	90·2	53·6	32·1	122·3

In addition there may be reckoned to be a further reserve of 40·0 million tons of smelting ore, and at Taberg in Småland another 50 million tons of titaniferous-iron ore from which about 15 million tons of concentrate may be obtained. The remaining resources of Dannemora and Persberg are about 6 million and 1·3 million tons of cobble ore respectively.

Zinc-Manganese Deposits of Franklin Furnace and Stirling Hill, New Jersey

LITERATURE

F. L. Nason. 'The Franklinite Deposits of Mine Hill,' Trans. Amer. Inst. Min. Eng. XXIV. p. 121.—P. Groth. 'Die Zinkerzlagerstätten von New Jersey,' Zeit. f. prakt. Geol., 1894, p. 230.—J. E. Wolff. 'Zinc and Manganese Deposits of Franklin Furnace,' Bull. 213, U.S. Geol. Survey, 1903.—J. F. Kemp. The Ore Deposits of the United States. New York, 1905, p. 231.—O. Stutzer. 'Die Zinkerzlagerstätte von Franklin Furnace in New Jersey,' B. u. H. Rundschau, No. 19, Kattowitz, 1908.

These deposits bear great resemblance to those which have just been described and especially to that of Långban. They are associated with an occurrence of crystalline limestone stretching from Orange Co., New York, across the north-western portion of New Jersey. This rock, in accordance with previous investigation by H. D. Rogers, was formerly regarded as Lower-Silurian, but according to the more recent surveys and fossil discoveries of F. L. Nason [1] it is more probably Cambrian. It lies upon gneiss and with this rock is intruded by granitic dykes to which both the metamorphism of the limestone and the formation of the ore are ascribed. The correctness of this interpretation of the genesis is however somewhat questionable.

The deposits at Mine Hill, near Franklin Furnace, and, two miles farther south, that of Stirling Hill, near Ogdenburg, are well known. At Mine Hill, magnetite occurs in the limestone in the immediate neighbourhood of the contact of this rock with gneiss, while the zinc or zinc-

[1] *Geology of New Jersey*, 1890, Vol. XIV.

manganese occurrences are found at somewhat greater distances from the contact. The deposit at Stirling Hill probably occurs at a somewhat higher horizon in the limestone. This rock in the neighbourhood of the ore is crystalline and contains crystals of graphite and pyrite such as are not found in the ore itself. The form of the ore-bed at Franklin Furnace may be seen from Fig. 251. It dips 40°–60° and varies in thickness between 7 and 37 m. though on an average it hardly exceeds 9 m. Among the ores, franklinite with 5·54 per cent of zinc and 7·5 per cent of manganese plays a large part; occasionally the zinc content of this mineral is considerably higher. In

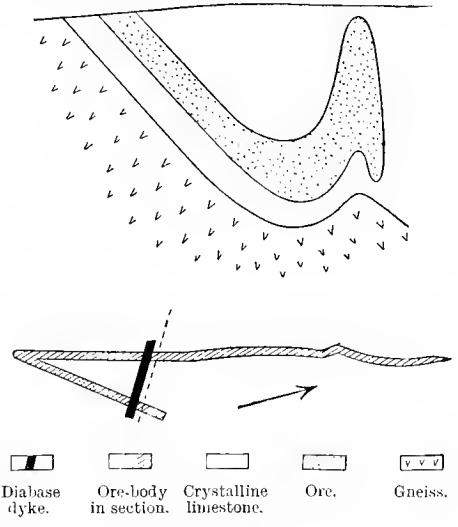

Fig. 251.—Plan and section of the deposit at Franklin Furnace, N.J. Nason.

addition, willemite with 58·5 per cent of zinc and zincite with 80·3 per cent, are found. The amount of manganese contained in the limestone is remarkable, reaching according to investigation by F. C. van Dyck as much as 16·57 per cent. In places, hornblende, augite, plagioclase, and different silicates accompany the ore, and now and then fluorite, rhodonite, axinite, sphalerite, chloanthite, etc. The occasional appearance of jeffersonite the zinc-manganese pyroxene, of tephroite the manganese-olivine $(Mn, Mg)_2SiO_4$, and of röpperite the manganese-zinc-olivine, is particularly interesting.

On an average the ore contains 11·06 per cent MnO, and 29·35 per cent ZnO, so that the deposits are equally those of zinc and manganese. The present yearly production is above 400,000 tons containing approximately 20 per cent of zinc. From this the zinc is first won leaving a residue

which contains about 12 per cent of manganese. The occurrence of manganese in this connection is so considerable as to influence the manganese production of the United States. To it the high outputs of manganese ore of earlier years in that country were due, such figures then not taking into account the low manganese content of the ore. The exemplary statistics now presented by *The Mineral Industry* have however since removed this reproach.

CONTACT-DEPOSITS CONTAINING CHIEFLY SULPHIDE ORES OF COPPER, LEAD, ETC.

The Copper Deposits of Arizona

LITERATURE

W. Lindgren. 'The Copper Deposits of the Clifton-Morenci District, Arizona,' U.S. Geol. Surv. Prof. Paper 43, 1905; Trans. Amer. Inst. Min. Eng., 1904; reviewed Zeit. f. prakt. Geol., 1906, p. 81.

In describing the important copper district of Clifton-Morenci, the second most important in Arizona, the works of Lindgren are followed. The oldest rocks in this district are pre-Cambrian granite and quartzitic schist, above which follows a sequence of Cambrian, Silurian, Devonian perhaps, Lower-Carboniferous, and Cretaceous beds. All of these are intruded by a number of eruptive rocks among which granite and quartz-monzonite, in part porphyritically developed, are most frequently represented. These are of late Cretaceous or of early Tertiary age. Younger than these again come lava-flows of basalt, rhyolite, and some of andesite, but these do not appear to have had any bearing upon the ore formation.

Where the granite and quartz-monzonite porphyries cross the Palæozoic limestones and slates they effect an intense metamorphism which is expressed in the formation of garnet, epidote, etc., while within the contact aureole itself, extending to a maximum distance of about 650 m. from the eruptive rock, important deposits of magnetite occur on the one side and sulphide deposits of copper and zinc on the other, the geological position of which is shown in Fig. 252. Since with increasing distance from the eruptive rock no further deposits are found, the conclusion may be drawn, as it was by Lindgren, that the material necessary for the formation of these deposits, within the inner ring, was supplied by the intrusion.

The ores occurring in the contact aureole, and especially in the garnetiferous material resulting from the alteration of the limestone, are chiefly magnetite, pyrite, chalcopyrite, and sphalerite. The beds in which these are found are often porous. In addition a large number of lodes

occur which, cutting equally the porphyry, granite, and sediments, contain in depth pyrite and chalcopyrite but have no content of sphalerite and magnetite. In the upper levels the Arizona copper deposits in general are intensely weathered with the formation of malachite, azurite, cuprite, chrysocolla, hemimorphite, willemite, etc.

The economically most important of these copper deposits at the

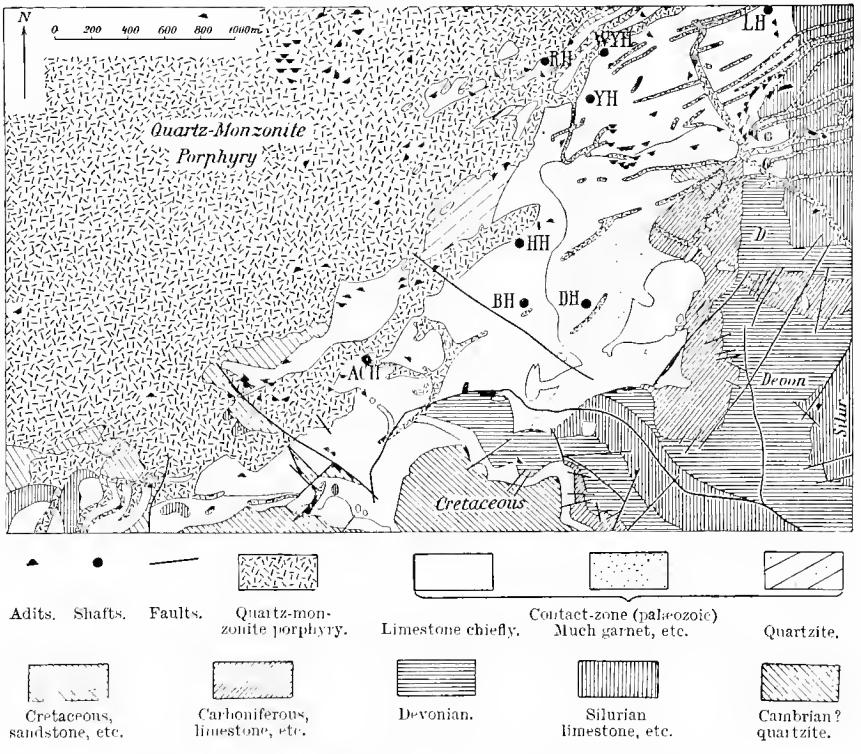

FIG. 252.—Geological map of the Morenci district, Arizona. W. Lindgren.

LH, Longfellow Hoist; WYH, West Yankee Hoist; RH, Ryerson Hoist; YH, Yavapai Hoist; HH, Humboldt Hoist; BH, Blue Hoist; DH, Detroit Hoist; ACH, Arizona Central Hoist.

present time are those of Bisbee, which likewise appear to be of contact-metamorphic origin,[1] an origin which according to L. D. Kellogg[2] may be taken to apply also to the copper deposits of the Cochise mining district in the south-eastern part of Arizona.

The Arizona copper deposits are among the most important in the world producing as they now do more copper than either the Montana

[1] F. L. Ransome, *Trans. Amer. Inst. Min. Eng.*, Feb. 1903.
[2] *Econ Geol.* I., 1906.

or the Lake Superior district. In 1908 Arizona produced 128,965 long tons of copper, Montana 114,040, while Lake Superior was only responsible for 99,000 tons. Copper mining in this State, leaving out of consideration unimportant operations still older, began about 1880, since when and until 1908, 1·1 million tons of metallic copper have been produced. Further comparisons with other districts have already been given on pp. 198–201.

According to W. H. Weed [1] the Cananea copper deposits in Mexico, near the frontier with the United States and some 80 km. south of Bisbee, are also of contact-metamorphic origin. Moreover M. B. Yung and R. S. McCaffery [2] regard those of the San Pedro district, New Mexico, as also being of this origin.

The important deposits of copper found in the neighbourhood of an occurrence of grano-diorite at Concepcion del Oro, Zacatecas, Mexico, and described not long ago by A. Bergeat,[3] were undoubtedly formed by contact-metamorphism. At this place four classes of deposits may be distinguished, namely: (1) metasomatic contact-deposits always carrying chalcopyrite; (2) the copper lode, El Placer-Weed, in grano-diorite; (3) lead-zinc deposits in limestone; (4) auriferous quartz lodes. Of these four, the first and second without doubt and the third in all probability, are genetically connected with the upheaval of the grano-diorite.

To the group of deposits here described, Weed [4] considers that the bronze-coloured copper ores found in limestone in the neighbourhood of a grano-diorite mass in the Boundary District of British Columbia also belong, while according to O. Stutzer [5] several other copper deposits, some lying on the west coast of British Columbia and others in Alaska, are also to be regarded as belonging to this class.

Contact-deposits of a peculiar type were recently described by J. F. Kemp and C. G. Günthur in a paper 'The White Knob Copper Deposits, MacKay, Idaho,'[6] as occurring in association with granite, quartz-porphyry, and limestone. The ore, accompanied by wollastonite, vesuvianite, epidote, etc., is found within the quartz-porphyry but only a hundred or a few hundred metres distant from the limestone. These deposits are columnar in shape and resemble chimneys.

[1] *Trans. Amer. Inst. Min. Eng.*, Oct. 1902.
[2] *Ibid.*, Oct. 1902.
[3] *Neues Jahrb. f. Min. B. B.* XXVIII., 1909.
[4] *Loc. cit.*
[5] 'Die kontaktmetamorphen Kupfererzlagerstätten von White Horse am Yukon, Kanada,' *Zeit. f. prakt. Geol.*, 1909.
[6] *Trans. Amer. Inst. Min. Eng.*, 1908; reviewed *Zeit. f. prakt. Geol.*, 1909, p. 180.

The Broken Hill Silver-Lead-Zinc Deposits

LITERATURE

E. F. Pittman. 'On the Geological Occurrence of the Broken Hill Ore Deposits, Records of the Geol. Survey of New South Wales, Vol. III., Pt., II. Sydney, 1892.—J. B. Jaquet. 'Geology of the Broken Hill Lode and Barrier Ranges Mineral Field,' Mem. Geol. Surv., New South Wales. Sydney, 1894; reviewed P. Krusch, Zeit. f. prakt. Geol., 1897, p. 94.—Bergeat. Written communication concerning Stelzner's view of the place in the classification of ore-deposits, to which the garnet-galena deposits of Broken Hill belong. Zeit. f. prakt. Geol., 1907, p. 314.—G. Eisfelder. 'Der Silber- Blei- und Zinkbergbau in Broken Hill,' Berg- u. Hüttenm. Zeit., 1898, Nos. 48-51.—R. Beck. 'Beiträge zur Kenntnis von Broken Hill,' Zeit. f. prakt. Geol., 1899, pp. 65-71.

The Broken Hill district in New South Wales lies to the south-east of Silverton. It consists chiefly of gneiss alternating on the one hand with quartzite, mica, and hornblende schists, and on the other with a quartz garnet rock. The age of these rocks is doubtful as all are greatly altered and no organic remains have yet been found in them; probably, if not still older, they are Lower-Silurian as C. S. Wilkinson considers them to be. The whole contorted complex is intruded by dykes of basic diorite and covered in greater part by beds belonging to the Recent and Pleistocene formations.

The famous deposits of Broken Hill though conformably intercalated in this complex, are of epigenetic nature. The four principal occurrences, which lie close together and in similar geological position, are known respectively as Main Broken Hill, Eastern Broken Hill, North Eastern Broken Hill, and Western Broken Hill. The principal deposit has the form of a saddle, for which reason and following the nomenclature of the Bendigo district these occurrences were formerly described as 'Saddle Reefs.' In consequence of this form the boundary between the oxidation and cementation zones, and that again between the latter and the primary zone, is more irregular than is usual with ordinary tabular deposits. Near the surface the entire occurrence consists of ironstone; below this, kaolin and oxidized ores appear; while deeper still it consists of sulphides and is principally a coarse-grained mixture of dark sphalerite and galena. No regular arrangement of these minerals can be observed, so that the primary ore may be described as of coarse intergrowth, though in consequence of the small size of the individual crystals this intergrowth becomes almost compact. Towards the foot-wall there is generally a sharp separation between the ore and country-rock whereas in the hanging-wall these pass insensibly from one to the other. In this latter direction also small conformable ore-bodies are sometimes found in the country-rock itself, though in such cases a connection with the main body is noticeable.

The manganiferous limonite at the outcrop of the Main Broken Hill

Lode is 20–120 feet wide and may be followed for one and a half miles. The Eastern Lode has the same form as the Main Broken Hill though, according to Jaquet, its actual cap has been removed by denudation and its western limb has been annihilated by pressure. The North Eastern Lode at its outcrop sometimes consists of a hard gossan and sometimes of a soft mixture of iron ore with quartz and alum minerals. The Western Lode has but a short western limb and its gossan contains cerussite and occasionally copper carbonates, which carbonates in general are rarely seen at Broken Hill.

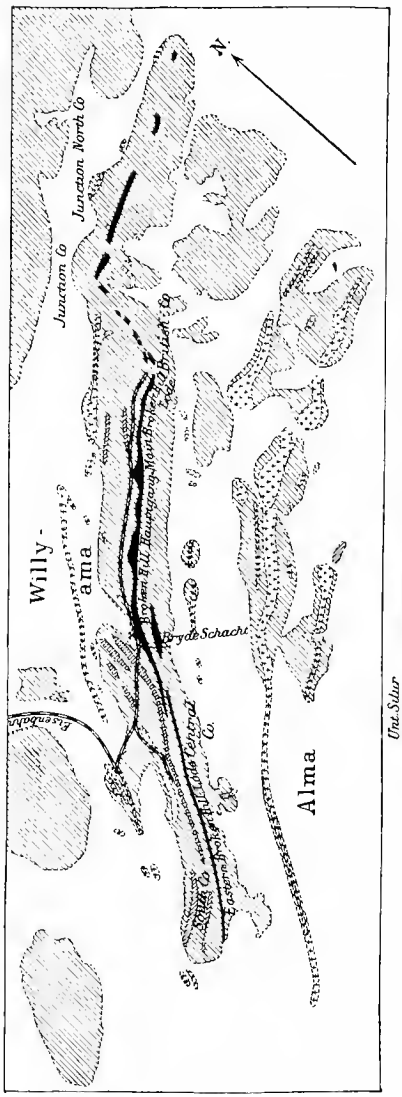

FIG. 253.—Geological map of the Broken Hill district; scale, 1 : 44,500. Jaquet.

The sulphide ores are galena, sphalerite, both intimately intergrown with quartz, garnet, felspar, and rhodonite; and more seldom pyrite, chalcopyrite, arsenopyrite, and fluorite. The galena and sphalerite both contain silver. A garnet-quartz rock containing 150–1800 grm. of silver per ton occurs together with the ore. The average ore contains 5–7 per cent of lead, 14–30 per cent of zinc, and 150–1200 grm. of silver per ton. The cementation ore forming but a narrow layer from 3 inches to 3 feet in thickness may assay as much as 8000 grm. of silver per ton with 12 per cent of copper.

The principal oxidized ores are limonite, hæmatite, psilomelane,

rhodonite, cerussite, cerargyrite, native silver, together with kaolinized felspar, garnet, etc. Smithsonite only occurs to a lesser extent. The lead carbonates contain 20–60 per cent of lead and 150–2500 grm. of silver per ton. High-grade 'dry ore' consisting of kaolin with some garnet-quartz, contains 120–9000 grm. of silver per ton with about 3 per cent of lead. Low-grade 'dry ore' usually has 150–1200 grm. of silver per ton.

As already mentioned, these Broken Hill occurrences were formerly regarded as saddle lodes which by lateral secretion had become filled with sulphide ores, this description having been put forward especially by Pittman and Jaquet. Krusch in reviewing the work of these two authorities is inclined to regard the deposits as true beds which have suffered folding and tilting in common with the surrounding gneiss. Bergeat endorses

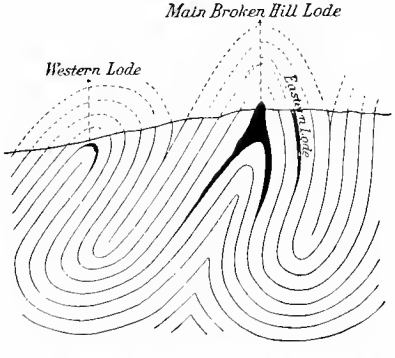

FIG. 254.—Section of the Main Broken Hill and the Western Broken Hill lodes. Jaquet.

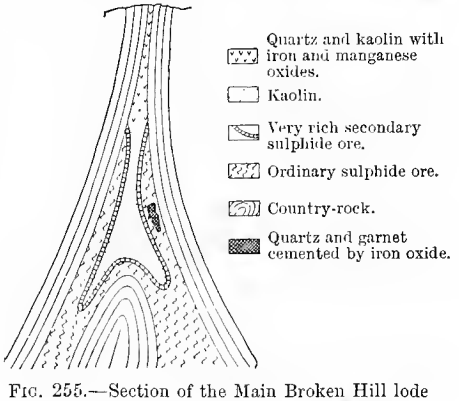
Quartz and kaolin with iron and manganese oxides.
Kaolin.
Very rich secondary sulphide ore.
Ordinary sulphide ore.
Country-rock.
Quartz and garnet cemented by iron oxide.

FIG. 255.—Section of the Main Broken Hill lode showing secondary depth-zones. Jaquet.

the view of Stelzner who also regarded these occurrences as ore-beds. In relation to their genesis, he compares them with Schwarzenberg in Saxony, Pitkäranta in Finland, Traversella in Piedmont, etc., and brings all these deposits together under a type which he designates as the Schwarzenberg-Persberg type corresponding, though on somewhat broader lines, with the pyroxene-garnet-pyrite-blende formation of Breithaupt. He remarks particularly however that this type of deposit is of all the most difficult to satisfactorily explain. Beck in the third edition of his book, basing his views upon the investigation of specimens, classes these deposits with the epigenetic ore-beds, as those specimens in his opinion contained evidence of a derivation from bedded lodes of the garnet subdivision of the pyrite-zinc-lead group in crystalline schists, the specimens exhibiting at the same time some metasomatic replacement of the country-rock. Bergeat in his *Lagerstättenlehre* placed them with the ore-beds.

The occurrence of typical contact minerals intimately intergrown with the ore, the undoubted epigenetic character of the deposits, and the great similarity they possess with such typical contact-deposits as those of Schwarzenberg, in our opinion justify for these Broken Hill lodes a place with the contact-metamorphic deposits, though it must be admitted that the question of their genesis is not thereby definitely settled.

The first discoveries in the district, namely of cerargyrite, were made in the year 1884, following which the town of Broken Hill was founded in 1886. From 1889 to 1896 the Broken Hill Proprietary Co., the most important company there, produced 290,000 tons of lead and 2·25 million kilograms of silver. The yearly lead production of the whole district amounts to about 117,000 tons or approximately one-ninth of the world's total. According to Krusch [1] that of the Broken Hill Proprietary in 1905 amounted to 67,062 long tons, while the Sulphide Corporation for the same year was responsible for 22,246 tons. In 1907 the figures were 54,168 tons and 22,394 tons respectively.

The silver production of the Broken Hill Proprietary in 1906 was 5,007,698 oz. or 155,700 kg. The district employs 9500 workers. On an average the ore at the 1100 ft. level, where the deposit is 65 feet wide, carries 17 per cent of zinc, 19 per cent of lead, and about 400 grm. of silver per ton.

The Contact-Deposits of Kupferberg in Silesia

LITERATURE

Websky. 'Über die geognostischen Verhältnisse der Erzlagerstätten von Kupferberg und Rudelstadt i. Schl.' Zeit. d. D. Geol. Ges. Vol. V., 1853, pp. 373-438.—P. Krusch, 'Die Klassifikation der Erzlagerstätten von Kupferberg i. Schl.' Zeit. f. prakt. Geol., 1901, pp. 226-229.—A. Sachs. Die Mineralschätze Schlesiens, 1906, p. 24.

These occurrences, the situation of which is indicated in Fig. 50, lie in that area of hornblende-schists which to the west is bounded by the biotite-granite of the Riesengebirge and to the north by the so-called 'green-schists.' The hornblende rocks, referred to by Websky as diorite-schists, strike generally about E.S.E. and dip steeply, sometimes as much as 85°, to the N.E. In composition and structure they often greatly resemble the hornblende-schists occurring at Schwarzenberg in Silesia as part of the contact rocks appearing there. Moreover within an intercalated bed of mica-schists Merensky, the mining engineer at one time in charge of the operations at Kupferberg, found an occurrence of spotted schists which he regarded as additional evidence of contact-metamorphism, while as these schists, broken through by quartz-porphyry, lie immediately on granite,

[1] *Untersuchung und Bewertung der Erzlagerstätten*, 1907.

probably no mistake is made if such contact-metamorphism be ascribed to that rock.

The ore-deposits in the neighbourhood of the granite, similar to those of Schmiedeberg also in Silesia, are bed-like. They sometimes carry magnetite with hornblende, epidote, etc., sometimes a mixture of magnetite with sphalerite and pyrite, and sometimes pure pyrite. To this group the Einigkeit Lode belongs, this consisting principally of pyrite, fibrous hornblende, prase-quartz, chlorite, pyrrhotite, and chalcopyrite. At Wolf's Shaft, rod-shaped crystals of lievrite intergrown with hornblende and magnetite have been found.

Farther from the granite and in the eastern portion of the district copper lodes occur, most of which have a gangue consisting chiefly of hornblende and chlorite, though others have quartz only. To the first belong the Abend Lode of Neuadler which strikes N.S. and dips 80° to the west; the Morgen Lode at the same place striking S.S.E. and dipping steeply to the east; and the Juliana Lode. The other lodes striking a little north of east form a group which is decidedly younger. Among these the Rosenstiel Lode belongs. The ores in both cases are chalcopyrite, bornite, etc. These in the upper levels had a considerable silver content.

FIG. 256. — Specimen from Kupferberg in Silesia with characteristic chlorite gangue and felspar; one-quarter natural size. Collection, *Geol. Landesanst.*, Berlin.

a, Chalcopyrite; *b*, chlorite; *c*, calcite; *d*, fluorite; *e*, felspar.

These Kupferberg deposits, with the exception of the younger lodes just mentioned, were formed by contact-metamorphism, which in this case therefore not only gave rise to deposits of the Schwarzenberg type but to lodes at the same time. It is unfortunate therefore that mining operations upon these interesting deposits have now practically ceased.

Iron ores and auriferous copper sulphides also occur together at a place called Springs situated on the river Calgour in Queensland at the

contact between granite and crystalline limestone and in a wollastonite garnet-quartz rock.

Reichenstein in Silesia

LITERATURE

R. B. Hare. 'Die Serpentinmasse von Reichenstein und die darin vorkommenden Mineralien,' Inaug. Diss., Breslau, 1879.—H. Güttler. 'Reichensteiner Arsenik,' Berg- und Hüttenwerk Reicher Trost, 1893.—Faulhaber. 'Die ehemalig schlesische Goldproduktion mit besonderer Berücksichtigung des Reichensteiner Bergreviers,' Inaug. Diss., 1896.—O. Wienecke. 'Über die Arsenerzlagerstätten von Reichenstein,' Zeit. f. prakt. Geol., 1907, p. 273; Heinzesche Chronik über die Bergstadt Reichenstein, 1817.—F. Pošepný. Archiv für praktische Geologie II., 1895, p. 322.—J. Roth. Erläuterung zur geognostischen Karte von Niederschlesien. Berlin, 1867.—C. Güttler. 'Über die Formel des Arsenikalkieses zu Reichenstein in Schlesien und dessen Goldgehalt,' Inaug. Diss., Breslau, 1870.

The occurrences at Reichenstein extend from the north slope of the Riesengebirge to the foot of the Jauersberg, and between the Schlacken and Glatz valleys. This area consists of mica-schists which to the south-east give place to gneiss and to the north-west alternate with hornblende-schist, syenite, and gneiss. The schists are all highly altered, much tourmaline now occurring in them. In the mica-schists near Reichenstein, varying thicknesses of limestone and serpentine occur accompanied by a large number of irregular ore-bodies or lenses. Of these the most important is an ore-bed worked by the Reicher Trost mine, the presence of which is marked on the surface by old workings extending 1200 m. in a south-west direction from the Esel Pit to the Follmersdorff Road. This bed is conformable to the enclosing schists and pitches 30°–40° to the south-west. The ore-body, which on the fourth level was proved to be 140 m. long, diminished in greater depth till on the ninth it was but 44 m. in length. The width in places reaches as much as 35 m. The peculiar form of this occurrence is probably due in great measure to disturbance. The ores, of which löllingite is the most important while arsenopyrite is subordinate, occur either as fine needles intimately intergrown with contact minerals, or in veins. Leucopyrite having a composition variously put at Fe_2As_3, Fe_3As_4, or Fe_3As_5, may also be distinguished. The gold content of these ores is important though it varies tremendously. Wienecke has placed that of leucopyrite at 28·6 grm. per ton, that of löllingite at 23·7 grm., and that of arsenopyrite at anything between 5·2 and 34·8 grm.

On account of their connection with serpentine these deposits were at times formerly regarded as magmatic segregations. As however they are only found in the contact aureole of the Jauersberg granite, and the presence of diopside, titanite, orthoclase, vesuvianite, apatite, and fluorite indicates a close connection between the eruptive rock and the deposits,

the authors, with Wienecke, consider that contact-metamorphism is the most probable genesis. At the first stage dolomite and dolomitic limestone were altered to diopside, the arsenides, and titanite, and then according to Wienecke, the limestone and diopside by later mineral solutions, became further changed to serpentine.

Mining operations began in the year 1270 when gold was the metal sought. Afterwards in the eighteenth century the deposits were exploited for arsenic, while it has only been since 1859, the year of the successful application of the chlorination process, that both the gold and the arsenic have been won. To-day at Reichenstein a considerable amount of arsenious acid, As_2O_3, is produced. The total production of this substance in Germany was in 1900 approximately 5000 tons.

STANNIFEROUS CONTACT-DEPOSITS

Pitkäranta in Finland

LITERATURE

O. Trüstedt. 'Die Erzlagerstätten von Pitkäranta am Ladogasee,' Bull. Comm. géol. Finlande, No. 19, 1907.—A. E. Törnebohm. Geol. Fören. Förh. XIII., 1891.

The country at Pitkäranta on the north side of Lake Ladoga consists of granite-gneiss of pre-Ladoga age conformably overlaid by Ladoga schists. Among these latter, hornblende-schist, mica-schist, gneiss, etc., and three beds of an impure limestone which in places contains much magnesia, are especially noticeable. It is within these limestone beds that the ore is principally found. All these rocks, as illustrated in Fig. 257, are intruded by a large occurrence of Rapakiwi granite of Jotnian age, termed the Ladoga Rapakiwi, which on surface has a length of 75 km. and a width of 30–45 km., in addition to which it is considered to extend as a flat laccolith beneath the covering of schists.

In the main, three classes of ore may be distinguished: (1) magnetite without titanic acid, with low amounts of manganese and phosphorus, but generally with 0·2–2 per cent of sulphur; (2) tin ore; (3) copper ore, chiefly chalcopyrite and pyrite, the latter with an amount of silver equal to about one five-hundredth that of the copper it contains. Sphalerite, galena, native bismuth, etc., also occur in small amount.

The deposits, though cassiterite and chalcopyrite occur to a smaller extent in dykes of granite-pegmatite and in impregnated schists, are found chiefly in limestone, with which speaking generally they are conformable, as indicated in Fig. 257. The most important of them, those for instance of the Omeljanoff-Klee complex in the old district of Pitkäranta, attain

a length which at times is as much as 800 m., while the width, which is generally 2–3 m., occasionally reaches 8–12 m. The ores are intergrown with skarn which here consists chiefly of salite, that is a variety of diopside, and garnet; with epidote, grammatite, vesuvianite, chondrodite, serpentine, quartz, calcite, etc., or more briefly the usual contact minerals.

Törnebohm in 1881 from the bedded character of the magnetite, drew the conclusion that this ore was of sedimentary origin, while he regarded the tin and the copper ores as of later formation. Trüstedt however

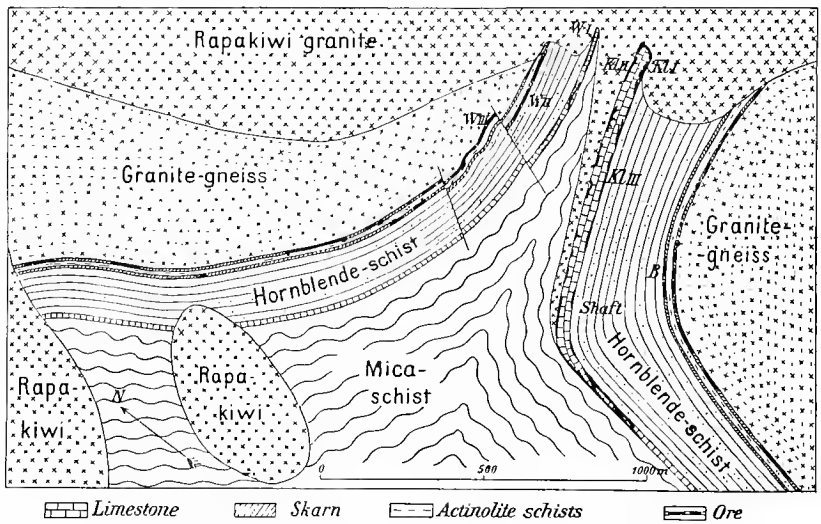

FIG. 257.—Map of the Hopunvaara field near Pitkäranta. Trüstedt.

WI, WII, WIII, Winberg I, II, III; *KI, KII, KIII,* Klara I, II, III; the shaft is at Hopunvaara; *B,* Beck.

considers the magnetite also to be epigenetic. It forms for instance pipe-like ore-bodies with crustification, similar to those illustrated in Fig. 60, a form of occurrence which postulates a gradual deposition of both ore and gangue from solution. The limestone moreover has been altered into ore more particularly along the fissures and fractures by which the solutions were able to penetrate. According to Trüstedt therefore all the ores have been formed by contact-metamorphic processes closely associated with the intrusion of the Rapakiwi granite.

The sequence of age is as follows: (1) magnetite; (2) cassiterite; (3) chalcopyrite. With the cassiterite, as is so often the case with tin ores, a subordinate amount of scheelite occurs. Topaz also has been seen, though only under the microscope, and with it fluorite. The

presence of greisen has also been observed here and there. The different stages in the formation of skarn and ore as interpreted by Trüstedt, are given in Fig. 258, where the several diagrams represent the assumed course of events in the case of the Klara series of the Hopunvaara district, which series carries iron ore only.

Mining which began in the beginning of the nineteenth century, after alternating periods of activity and idleness, finally stopped in 1904. The total production from 1814 has been some quarter million tons of iron ore, 6617 tons of copper, 11·2 tons of silver, and 489 tons of tin. The total amount of ore hoisted in the old district has been 883,380 tons; in the new district 34,383 tons; in the Hopunvaara district 34,164 tons; and in the Lupikko district 147,585 tons. The first of these districts was almost exclusively the source of the copper and tin, while the last three were to an equal extent responsible for the iron.

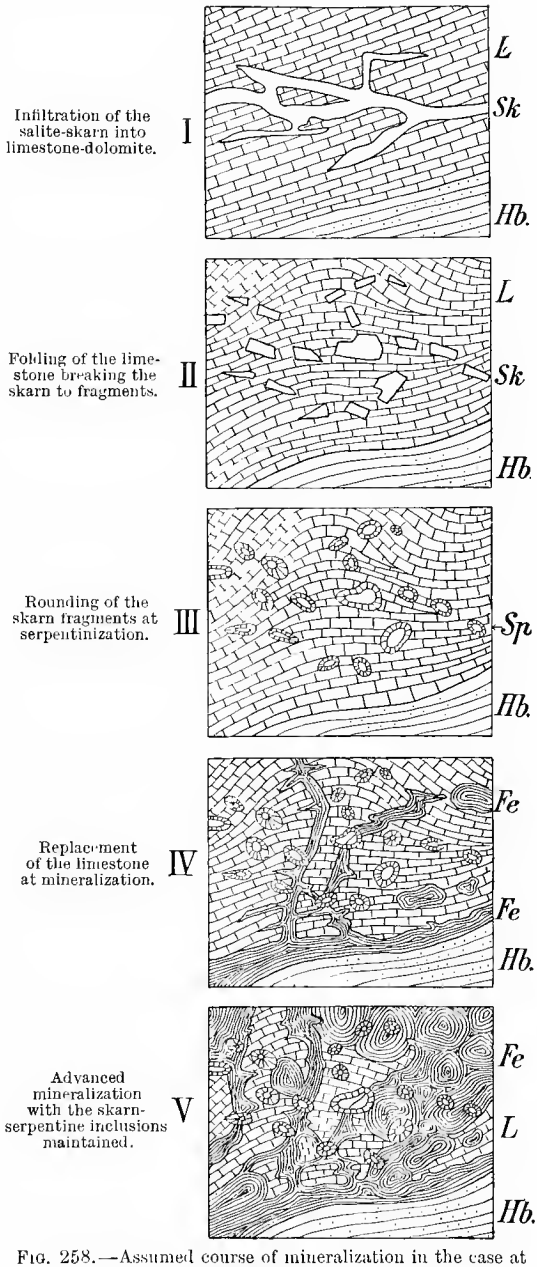

FIG. 258.—Assumed course of mineralization in the case at the Pitkäranta contact-deposits. Trüstedt.

L, Limestone; *Sk*, skarn; *Sp*, serpentine; *Fe*, iron ore; *Hb*, hornblende-schist.

Swarzenberg in the Saxon Erzgebirge

LITERATURE

Freih. von Beust. 'Ueber die wahre Bedeutung der sogenannten Erzlager bei Schwarzenberg,' Cotta's Gangstudien III., 1860, p. 244.—H. Müller. 'Der Erzdistrikt von Schneeberg,' ibid. p. 177.—F. Schalch. Erläuterung zur Sektion Schwarzenberg der geologischen Spezialkarte; ore-deposits mapped by H. Müller, 1884.—K. Dalmer. 'Die Erzlager von Schwarzenberg im Erzgebirge,' Zeit. f. prakt. Geol., 1897, p. 265.—R. Beck. 'Über die Erzlagerstätten von Schwarzenberg,' Zeit. d. D. Geol. Ges., 1900, pp. 58-60; 'Über die Erzlager der Umgebung von Schwarzenberg,' Pt. I., Jahrb. f. d. Berg- u. Hüttenw. im Königr. Sachsen, 1902, pp. 51-87; Pt. II., ibid., 1904, p. 56.

The country at Schwarzenberg, going from hanging-wall to foot-wall, consists of parallel folds of phyllite, mica-schist, and augen-gneiss, which at Rackelmann and Galgenberg are broken by granite, the intrusion of which was accompanied by extensive contact-metamorphism. Into the question of the ore-deposits the mica-schist formation alone enters.

These deposits, it is interesting to note, are arranged in two concentric rings around the granite, which rings coincide with occurrences of metamorphic crystalline limestone and dolomite. The deposits are further accompanied by pyroxene represented by salite, by amphibole, and to a lesser extent by garnet, quartz, epidote, chlorite, mica, fluorite, vesuvianite, etc. The general geological position of the occurrence is shown in Fig. 47.

Beck considered the bedded and banded occurrences of magnetite in the limestone and in the salite-actinolite rock as being the most important, though at the same time sulphide zinc-lead-copper ores and silver-cobalt ores occur as well as those of tin. In consequence of the intimate intergrowth of the magnetite with these different minerals the ore mined changes so much that many a mine has at different times of its existence been worked successively for iron, for copper, or for argentiferous lead. The ore occurs either as compact masses or as veins occupying the interstices between the silicates.

F. Schalch and A. W. Stelzner regarded these deposits as Archæan, and formed simultaneously with the mica-schist. K. Dalmer, as the result of investigation in 1897, came to the conclusion that the deposits stood genetically in close connection with the contact-metamorphism occasioned by the granite intrusion, a view in agreement with that formerly advanced by von Beust and H. Müller. According to Beck the true contact minerals to be seen are somewhat older than the ores, which latter appear to have been formed at the same time as the quartz and fluorite. The arrangement of the ore in shoots related to fissures is remarkable.

In the St. Christoph mine near Breitenbrunn an extensive lode of löllingite occurs. In this same neighbourhood particularly, cassiterite also

is found, this ore probably having resulted by impregnation from the above-mentioned fissures.

Berggiesshübel

LITERATURE

R. Beck. Erläuterungen zu Sektion Berggiesshübel der geologisehen Spezialkarte von Sachsen. Leipzig, 1889, p. 25.—H. Müller. Über die Erzlagerstätten der Umgegend von Berggiesshübel. Leipzig, 1890.

Berggiesshübel lies among the hills of the Elbe valley in south-east Saxony. The country consists of phyllite and of Devonian beds intruded by granite bosses of which the Markersbach granite is that best known. These intruded beds, particularly the Devonian, are highly altered by contact-metamorphism, while the granite itself is traversed by bands of zwitter. The hornstone, hornschiefer, knotted-schists, actinolite schists, and the salite-garnet rock derived from beds of limestone alternating with schalstein and now found associated with the beds of magnetite, are widely known. With the magnetite, sulphide copper ores such as chalcopyrite, bornite, chalcocite, and tetrahedrite occur, and more seldom, galena, sphalerite, arsenopyrite, and pyrite. An interesting feature of this occurrence is that, just as was the case at Kupferberg, lode-like deposits of copper ore accompanied by stanniferous veins are known. Berggiesshübel forms therefore a connecting link between Kupferberg and Schwarzenberg.

Limonite and cassiterite are also found together in a Mesozoic limestone at Cava del Fumacchio near Campiglia in Tuscany. In the neighbourhood of this occurrence B. Lotti has demonstrated the existence of a mass of tourmaline-granite probably of post-Eocene age.[1]

The Ore-Deposits at Campiglia Marittima, Tuscany

LITERATURE

G. von Rath. 'Die Berge der Campiglia in der toskanischen Maremme,' Zeit. d. D. Geol. Ges., 1868, Vol. 22, p. 307.—B. Lotti. 'Le Roccie eruttive feldspatiche di Campiglia Marittima,' Boll. del R. Comit. geol., 1887, Nos. 1 and 2; 'Sulla Genesi dei giacimenti metalliferi di Campiglia Marittima,' Boll. del R. Comit. geol., 1900, No. 4.—Alfred Bergeat. 'Beiträge zur Kenntnis der Erzlagerstätten von Campiglia Marittima (Toskana) insbesondere des Zinnsteinvorkommens dortselbst,' Neues Jahrb. f. Min. Geol. Pal., 1901, I. p. 135.

These deposits lie in a zone 5 km. long, which extends from Monte Valerio to Monte Calvi, these hills being respectively 264 m. and 646 m.

[1] B. Lotti, *Boll. Com. geol.*, 1887; A. Gurlt, K. Dalmer, *Zeit. f. prakt. Geol.*, 1894, pp. 324 and 400 respectively.

high. Bergeat distinguished two groups; the first, lying some 2 km. north-west of the town, being stanniferous; and the second at a distance of about 4 km. carrying the sulphide ores galena, sphalerite, pyrite, and chalcopyrite, these ores having been mined at Temperino, near Rocca San Silvestro, and at Casa Lanzi.

The sulphides are found in the neighbourhood of quartz-trachytes, and are associated with such contact minerals as epidote, chlorite, lievrite, manganiferous pyroxene, quartz, and felspar. They occur in the closest connection with fissures and joints in Triadic and Liassic limestones which have been altered to marble by the intrusion of the eruptive rock. No doubt therefore exists that these are contact-deposits.

The tin deposits of Monte Valerio and Monte Fumacchio are found in a reddish limestone belonging probably to the Middle Lias, and are overlaid

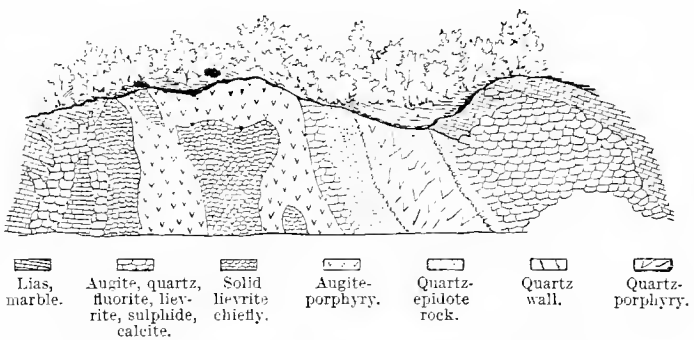

FIG. 259.—Section at the Coquand Shaft, Temperino near Campiglia. Bergeat.

by slates of the Upper Lias. The tin is associated with limonite which occurs either as a true lode-filling in the slates or as a metasomatic deposit in the limestone. Sometimes a connection with fissures may be established, but at other times the occurrences are quite irregular and no such connection is apparent. The limonite according to determinations by Bergeat contains 44–59 per cent of iron, 0·11–0·29 per cent of manganese, a little aluminous impurity, and a distinct phosphorus content; presumably therefore it represents altered pyrite. Cassiterite often appears at Monte Valerio in the south-west portion of the district, but at Cava Gotti and Temperino on the other hand, the limonite is free from tin. Wherever found the distribution of the cassiterite is irregular. Bergeat found crystalline aggregates arranged parallel to the walls, though not in layers sharply distinct from the limonite. It is of interest to observe that this cassiterite bears no resemblance to the variety known as wood-tin.

Although these deposits but little resemble the well-known types

of tin deposits, and may only be compared with those tin lodes in the Malay Peninsula which occur in limestone and are distinguished by carrying

Fig. 260.—Stanniferous limonite from Cento Camerelle near Campiglia. Bergeat.

pyrite, nevertheless, containing tin as they do, they may be regarded as connecting links between the contact-deposits on the one side and the tin deposits proper on the other.

LODES, IRREGULAR CAVITY-FILLINGS AND METASOMATIC DEPOSITS

The Tin Lodes

LITERATURE

A. Daubrée. 'Sur le gisement, la constitution et l'origine des amas de minéral d'étain,' Ann. des mines 3, XX., 1841; Études synthétiques de géologie expérimentale. Paris, 1879. —Elie de Beaumont. 'Notes sur les émanations volcaniques et métallifères,' Bull. de la Soc. Géol. de France 2, IV., 1847.—E. Reyer. Zinn, eine geognostisch-montanistisch-historische Monographie. Berlin, 1881.—J. H. L. Vogt. 'Über die durch pneumatolytische Prozesse an Granit gebundenen Mineralneubildungen,' Zeit. f. prakt. Geol., 1894; 'Über die Zinnsteinganggruppe,' ibid., 1895.—H. Louis. 'The Production of Tin,' Mining Journal, London, 1899.—F. L. Hess and L. D. Graton. 'The Occurrence and Distribution of Tin,' U.S. Geol. Survey, 1905, Bull. 260.—S. Fawns. 'Tin Deposits of the World,' London, 1905.—J. Roth. Allgemeine und chemische Geologie, III., 1890.—F. Zirkel. Lehrbuch der Petrographie, II., 1894.—H. Rosenbusch. Microskopische Physiographie der Gesteine, 1908.—W. Lindgren. 'Metasomatic Processes in Fissure-Veins,' Trans. Amer. Inst. Min. Eng., 1900.—A. von Groddeck. 'Über die Zinnerzlagerstätte des Mount Bischoff in Tasmanien,' Zeit. d. D. Geol. Ges., 1884, 1886, 1887.—W. von Fircks. Ibid., 1899.—W. Salomon and H. His. 'Körniger Topasfels im Greisen bei Geyer,' ibid., 1888.

Tin lodes are characterized by their constant connection with granite or exceptionally with the dyke and lava equivalents of granite; by their richness in fluorine- and boron minerals; and finally, by the pneumatolytic metamorphism of the country-rock resulting in the formation of greisen. The lodes themselves have been filled by pneumatolytic processes representing the after-effects of the granite intrusion, whence it follows that the characteristic minerals of this filling were without doubt derived from the granite while this was still in a molten condition, probably by the action of dissolved fluorides, etc.

As pointed out by A. Daubrée and Elie de Beaumont as far back as the 'forties and later confirmed by numerous other authorities, true tin lodes—the tin-silver lodes of Bolivia not being regarded as therein included —whether they occur in the Erzgebirge or the Fichtelgebirge of Germany; in Cornwall, Brittany, Central France, Spain, Portugal, Finland, Malacca, or the East Indies; in the different Australian States or South Africa;

in North America or the Argentine,—are all connected with granite. Exceptionally, at Mount Bischoff in Tasmania and at Durango in Mexico the connection is with quartz-porphyry and rhyolite, these two rocks representing respectively the dyke and lava equivalents of plutonic granite. Since tin lodes are generally found partly in the country-rock immediately surrounding granite and partly in the peripheral portions of the granite itself, their derivation as contact effects of acid eruptive rocks is evident. The further fact that hitherto tin lodes have nowhere been found genetically dependent upon basic rocks undergoing consolidation, is also deserving of emphasis.

Mineralogically, tin lodes are remarkable for their striking uniformity. The characteristic gangue minerals are quartz and different fluorine-, boron-, and phosphorus minerals. Among these, fluorite and lithia-mica are the most frequent, the latter being represented by the two minerals zinnwaldite and lepidolite, both of which contain fluorine. Other micas also occur but less frequently. Tourmaline the boron-silicate is also frequent, after which come axinite and datolite; topaz, occasionally developed as pyknite; apatite and such other phosphates as amblygonite, triphyline, monazite, etc.; and less frequently beryl, phenakite, gilbertite, nacrite, steinmark, and kaolin, the latter minerals being secondary. Barite, calcite, etc., occur but seldom. Among ores, the most frequent companion of cassiterite is wolframite, while the other wolfram minerals scheelite and stolzite, the at-times auriferous sulphides arsenopyrite and pyrite, the sulphide copper ores, bismuth- and uranium ores, specularite, and magnetite, are in general more seldom, though exceptionally the last-mentioned iron minerals are of frequent occurrence in the Straits Settlements and the East Indies. Now and then, columbite, tantalite, rutile, anatase, etc., are found, while in some lodes stannite occurs sparingly. Genetically the boron-tin mineral, pageite, recently demonstrated by A. Knopf [1] to occur in the tin district of Alaska, is highly interesting.

Stolzite, the lead-wolframate, is certainly always secondary, as is also scheelite the lime-wolframate, and such phosphates and arsenates as wavellite, lime-uranite, copper-uranite, pharmaco-siderite, etc.

Minerals containing fluorine, such as fluorite, different micas, topaz, tourmaline, fluor-apatite, etc.; containing boron, such as tourmaline, axinite, datolite, zinnwaldite and lepidolite; phosphorus, such as apatite and other phosphates; wolfram and lithium, such as lithia-micas, sometimes also spodumene, lithia-tourmaline, and the lithia phosphate, triphyline; beryllium, such as beryl and phenakite; arsenic and sulphur, subordinately; uranium, niobium, tantalum, molybdenum, etc., rarely; and finally in some districts copper also, are especially distinctive of tin lodes.

[1] *U.S. Geol. Surv.* Bull. 358, 1908.

Another distinguishing feature of these lodes is the alteration of the immediate country-rock to greisen, mica-rock, quartz-rock, luxullianite, tourmaline-rock, topaz, zwitter, cassiterite, and such like; and in some

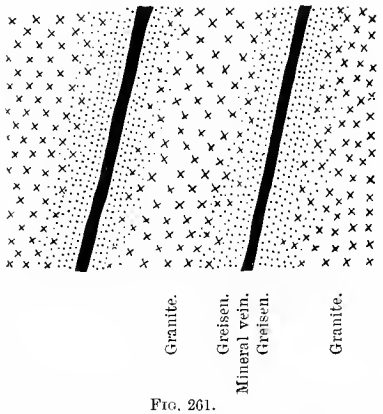

Fig. 261.

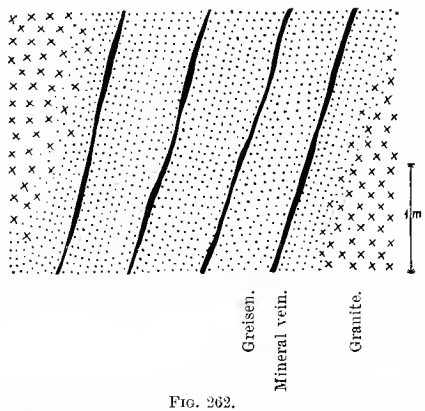

Fig. 262.

Figs. 261, 262.—Showing the relation of cassiterite veins, greisen, and granite in Cornwall. Neve Foster.

districts also to kaolin. Such alteration is illustrated in Figs. 261 and 262, the latter indicating the complete transformation of the rock between two veins when these occur close together. It results more usually in the formation of greisen, a rock consisting chiefly of quartz and mica

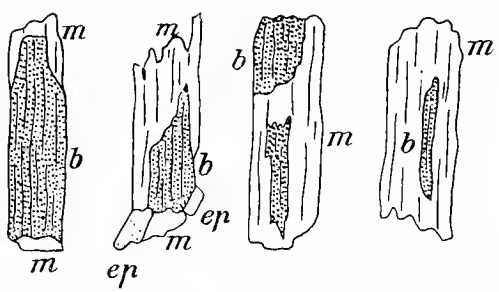

Fig. 263.—Showing the alteration of biotite (*b*) to muscovite (*m*) with the separation of epidote (*ep*); magnified ten times. Vogt.

with some cassiterite. In this alteration the felspar particularly is destroyed, though at the same time the magnesia-mica is altered to lithia-mica or to potassium-mica, this latter change being illustrated in Fig. 263.

The effect of this alteration upon the chemical composition of the rock may be gathered from the analyses given on the next page. Of those, Nos. 1*a* and 1*b* are from Altenberg, after K. Dalmer; while Nos.

2*a*, 2*b*, and 2*c* are from New England, New South Wales, after L. A. Cattou. A comparison of these analyses shows that the change, at least very often, consists in the removal of Na_2O and K_2O especially, and to a less extent of CaO and MgO, while on the other hand some iron appears to be introduced. Mineralogically the greisen No. 1*b* consists of 50·28 per cent of quartz, 12·14 per cent of topaz, 36·8 per cent of mica, and 0·43 per cent of cassiterite, indicating that in this case a remarkable alteration has taken place mineralogically without any substantial amount of material having been either removed or added. Cases there are in number however where a thorough chemical rearrangement has been accompanied by the addition of some constituents and by the complete or almost complete removal of others. With strong silicification a quartz-rock is formed ; with the plentiful formation of mica,

	Granite No. 1*a*.	Greisen No. 1*b*.	Granite No. 2*a*.	Greisen Intermediate Stage No. 2*b*.	Greisen No. 2*c*.
SiO_2	74·68	70·41	76·69	75·42	78·47
TiO_2	0·71	0·49	...	0·15	0·22
SnO_2	0·09	0·49 [1]	...	0·22	0·08
Al_2O_3	12·73	14·86	10·89	12·98	11·50
Fe_2O_3	...	1·42	0·76	1·66	2·64
FeO	3·00	5·09	0·39	0·58	1·05
MnO	...	0·29	...	...	...
MgO	0·35	0·09	0·18	0·23	0·49
CaO	0·09	0·21	1·73	0·10	Trace
K_2O	4·64	3·01	2·97	1·62	1·17
Na_2O	1·54	0·98	5·35	3·05	1·99
F	...	3·10	... [2]	... [2]	... [2]
H_2O	1·17	...	0·50	1·78	1·40
FeS_2	...	...	...	1·69	0·80
Total	99·50	100·44	99·46	99·48	99·81

[1] As cassiterite 0·43, in mica 0·06. [2] Presence not established.

a mica-rock ; while with boric acid in large amount tourmaline-rock arises. Of particular interest in this connection is the phenomenon of topazification, that is the more or less advanced alteration of the country-rock along the lodes to topaz. This has been established in more than one occurrence. Valuable information concerning the topazification of the quartz-porphyry at Mount Bischoff has been given by von Groddeck and von Fircks ; concerning that at Geyer in Saxony, by Salomon and His ; and concerning that at Altenberg-Zinnwald, by Dalmer. Schröder[1] has lately described the Topaz-Brokenfels and the topazified porphyry of Schneckenstein in Saxony; while the topaz-rock of Auerbach, likewise connected with tin lodes, was described by Breithaupt as far back as 1854. Finally, at times a fluoritization of the country-rock, consisting in the formation of much fluorite, takes place.

[1] *Erläuterung zur geologischen Karte von Sachsen*, Blatt Falkenstein.

When a notable amount of cassiterite is introduced and arranged in fine-grained modifications in greisen, the rock is known as 'zwitter,' a designation which gives way to that of 'tin-rock' when the tin content is still higher. Not infrequently the greisen, or the altered rock whatever it may be, is strongly impregnated with cassiterite, while the vein itself, as illustrated in Fig. 264, is limited to a narrow fracture. Such a fracture having provided the means of access for the material forming the impregnation, is known as an 'impregnation fracture.'

With such alteration of granite to greisen, mica-rock, etc., complete pseudomorphs of the constituent minerals are often to be observed. The best known are those of cassiterite and to a less extent those of quartz, after felspar. Such have been found at different places in Cornwall. Those of tourmaline after felspar, of cassiterite and topaz after quartz, etc., also deserve mention. Such pseudomorphs indicate that the alteration of the rock in which they occur must have proceeded by metasomatic processes when the rock was already solid.

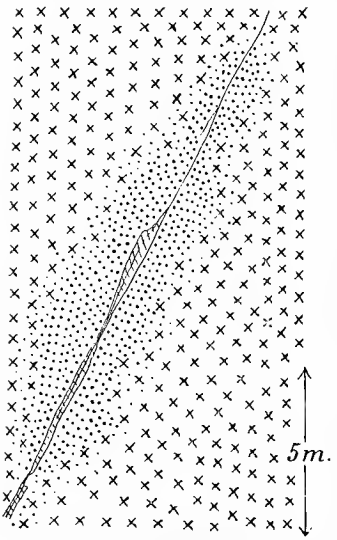

FIG. 264.—Impregnation fracture with concomitant greisen formation in granite. Collins.

Curiously enough the cassiterite crystals of different fields exhibit divergent habit, sometimes widely so. In this connection F. Becke [1] distinguished the following three types: (1) the Erzgebirge type of thick short crystals almost all twinned, often with twins repeated, and sometimes many times repeated; (2) the Cornwall type of slender prisms, the habit of needle-tin; (3) the Pitkäranta type of ditrigonal pyramids and prisms, twins seldom occurring. W. Kohlmann [2] has however shown that such a division cannot always be insisted upon, as transition and intermediate types appear. The cassiterite from the Straits Settlements for instance, in so far as the habit of its crystals is concerned, stands between the Erzgebirge and the Cornwall types.

Tin ore occurs not only in true lodes but also occasionally along original joints and contraction-planes. The ore for instance in some of the Erzgebirge mines within the granite area, is found upon horizontal or gently inclined planes. The deposits at Zinnwald illustrated in Fig. 265

[1] *Tschermaks Min. Mitt.*, 1877.
[2] Groths, *Zeit. f. Krist. u. Min.* XXIV., 1895.

furnish excellent examples of such an occurrence. At that place no less than sixteen of such deposits, individually up to one metre in thickness and with symmetrical filling, are found one above the other. These on account of their horizontal lay are termed *Flöze* (Seams) by the miners in Germany, a term equivalent to the ' tin-floors ' of Cornwall.

At other places, as illustrated in Figs. 261 and 262, the tin ore is found more often or entirely along the vertical joints; while at others again it occurs both along the vertical as well as the horizontal joints or along any other plane whatever. Occurrences of this last type are referred to as ' stock-works.' They are characteristic of the Erzgebirge, being found for instance at Altenberg, Geyer, and elsewhere. In Cornwall also they are represented, and they have also been described at Morbihan in France.

Tin lodes, as illustrated in Fig. 146, often show a characteristic crusted structure with mica, etc., at the walls, and quartz and ore in the middle. A symmetrically repeated crustification, such as occurs with many of the

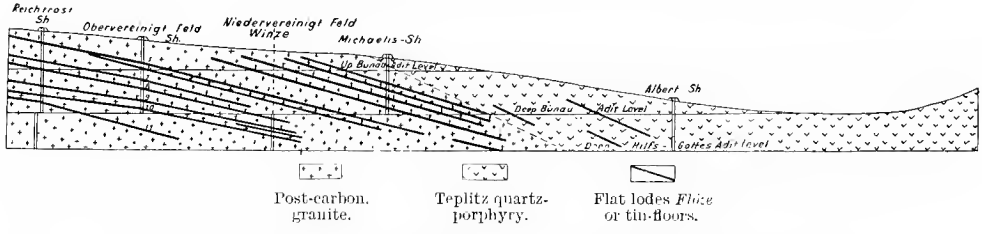

Fig. 265.—Section through the northern portion of the Zinnwald granite area.
Blatt Zinnwald der geol. Spezialkarte von Sachsen.

lodes of the lead-silver group, is however not often seen.

As already mentioned on p. 154, tin oxide in small quantities has repeatedly been found upon analysis in granite itself or in one or other of the constituent minerals of that rock, under circumstances which absolutely preclude the possibility that such oxide could have been mechanically involved with the mineral analyzed. This has been particularly the case with some micas, but also with felspar. The amount of such tin is extremely small, seldom reaching 0·05 per cent. In some granites also, and where there could be no question of secondary impregnation into a consolidated rock, primary occurrences of cassiterite in minute crystals may be observed, such as must have arisen by crystallization from a granite magma. It is of course possible however that in these cases by pneumatolytic processes the tin oxide was introduced into the magma either before or during its consolidation. In like manner the occasional and at times abundant occurrence of cassiterite, wolframite, columbite, topaz, etc., in dykes of pegmatitic granite, may probably be explained.

With these dykes the phase of magmatic consolidation can be differentiated from that of the entry of pneumatolytic compounds. In this connection reference is recommended to the paper by W. C. Brögger upon the augite-syenite and nepheline-syenite pegmatite dykes of southern Norway,[1] and to his work upon the minerals contained in them.[2]

The minerals associated with tin lodes are occasionally found in the druses of granite and then in such a manner as to suggest that they were only formed at a comparatively late stage in the process of consolidation. V. Dürrfeld,[3] from the minerals in the druses of Waldstein granite from the Fichtelgebirge, was able to distinguish the following generations: (1) crystals of potassium felspar, albite, and quartz, solidified from the magma; (2) zinnwaldite, topaz, tourmaline with axinite, and cassiterite, derived from the magma by pneumatolysis; (3) muscovite, secondary albite, gilbertite, secondary tourmaline, secondary potassium-felspar and younger quartz, probably deposited from the water circulating in the rock; (4) herderite, apatite, fluorite, and euclase; and finally (5) barite, chalcopyrite, lime-mica, copper-uranium-mica, etc.

As already mentioned, tin is essentially an element characteristic of the acid eruptive rocks in their various facies, an association which may be explained by the chemical analogy between SiO_2 and SnO_2. As pointed out long ago by Daubrée and Elie de Beaumont, from this constant association the conclusion may be drawn that the formation of these lodes is genetically regularly dependent upon these acid rocks. They must therefore be regarded as endomorphic and exomorphic contact phenomena formed at the conclusion of the period of eruption, yet occasionally crossed by later granitic and quartz-porphyritic dykes, the expiring efforts of a subsiding magma. From these considerations as well as from the striking abundance of fluorine- and boron minerals, the above-mentioned authorities further concluded that the tin lodes arose by emanations from acid magmas, or in other words that they represent a particular kind of pneumatolytic contact phenomena. That in such a process of formation fluorine and boron were the vehicles by which the minerals were conveyed Daubrée convincingly showed in his well-known sublimative syntheses. It is recalled that by these he succeeded in artificially forming cassiterite, rutile, specularite, apatite, and a compound having the composition of topaz. These experiments, together with various geological observations, render it highly probable that the minerals associated with tin were formed from compounds circulating in the lode-fissures and principally from the compounds of fluorine, such as hydrofluoric acid, stannic-fluoride,

[1] Groths, *Zeit. f. Krist. u. Min.* XVI., 1890.
[2] *Ges. d. Wiss.*, Christiania, 1906.
[3] *Zeit. für Krist. u. Min.* XLVI., 1909.

boron-fluoride. Since the presence of chlorine has not only been established in apatite, but also in the micas of some tin lodes, it is probable that the fluorine under these circumstances was often accompanied by a small amount of chlorine.

The characteristic alteration of the country-rock along tin lodes may accordingly be also ascribed to a pneumatolytic metamorphism effected principally by the different compounds of fluorine circulating in the fissures. The pseudomorphs of cassiterite after felspar may for example be explained in that the hydrofluoric acid, released by the dissociation of stannic fluoride according to the formula $SnF_4 + 2H_2O = SnO_2 + 4HF$, attacked and decomposed the felspar, while at the same time the space vacated became occupied by the stannic oxide, deposited as cassiterite.

Concerning the association of the compounds circulating in the fissures, it must be remembered that with many of them the critical temperature is already passed at a relatively low temperature. This temperature for CO_2 and HCl lies below 100° C.; for H_2S, SO_2, CO, NH_3, between 100° and 200°; for CS_2, PCl_3, $SiCl_4$, between 200° and 300°; and for H_2O, $AsCl_3$, $SiBr_4$, $SnCl_4$, $TiCl_4$, between 300° and 400°. Should the mineralization have taken place at a temperature higher than 400°, which appears probable seeing that this phenomenon belongs to the period of eruption, no difference could have existed between the gaseous and the liquid condition; indeed at a temperature of 300° even under conditions of enormous pressure, most of the above compounds would no longer have been able to exist in the liquid state. Were moreover such aqueous solutions present it is nevertheless certain that vapours and gases played a very essential part in the formation both of the lodes and of the greisen.

The theory here briefly sketched, supported as it is by a wealth of mineralogical and geological facts and explained by the beautiful mineral-syntheses of the French investigators, has been further developed and confirmed in the last decades by a number of younger workers, till in its broad lines it enjoys the approval of by far the greatest number of those who have studied the subject. It is not surprising therefore that it has exerted a remarkable influence upon the general development of the science of Geology.

Other hypotheses, for example that of E. Reyer, who regards tin-bearing greisen as primary streaks marking later injections of the original magma, or that of Sandberger, according to which the tin lodes became filled by lateral secretions from the country-rock, have undoubtedly proved to be erroneous. Again, when G. Bischof[1] assumed that the materials holding the stannic acid in solution in the fissures were the carbonates of the alkalies and alkaline earths so widely distributed in underground waters, and when he further found in the felspar of the granite the very

[1] *Lehrb. der chem.-physik. Geol.*, 1866, pp. 811-824.

substance which by its decomposition provided this necessary solvent, he propounded a hypothesis which left the constant association of tin ores with fluorine- and boron minerals unexplained.

Vogt in 1895, applying the theory emanating from the French school, endeavoured to determine the nature of the dependence of the tin lodes upon acid magmas and to explain the concentration in these lodes of the elements which characterize them, such for instance as tin, boron, lithium, phosphorus, fluorine, etc. This endeavour consisted chiefly in a comparison between the tin lodes and the Norwegian apatite lodes described in the next section. Between these two groups the most important analogies are as follows:

1. Each group is characterized by its association with a particular eruptive rock, the tin lodes with granite, the apatite lodes with gabbro.

2. In both cases the lode material is younger than the rock in which it occurs, though in both cases the interval between the consolidation of the eruptive and the formation of the lode was small. Evidence of this lies in the fact that both classes of lode are occasionally intruded by apophyses or late injections of the particular magma.

3. Both groups are regularly marked by a pneumatolytic metamorphism of the country-rock, which in the one case is characterized by the formation of greisen, etc., and in the other by that of scapolite rocks, these latter resulting from the gabbro by the addition of sodium chloride.

4. Mineralogically, among other properties, the analogy rests upon the occurrence of apatite and allied phosphates in both cases, with this difference however, that while with the apatite lodes the principal mineral is a phosphate, with the tin lodes the phosphates play but a subordinate part. In spite of this subordination however, apatite still remains a characteristic feature of tin lodes, since practically speaking it does not occur in lead, silver, zinc, and gold lodes, these not having been formed by pneumatolysis. In the apatite lodes the stannic acid of the tin lodes is replaced by titanic acid. In both groups the principal gangue minerals are silicates wherein these lodes differ from the lead-silver lodes. In the place of the quartz, alkali-mica, tourmaline, topaz, beryl, etc., which are associated with tin lodes, magnesia-mica, enstatite, hornblende-scapolite, etc., occur with the apatite lodes.

5. With each group one halogen element occurs plentifully, fluorine with the tin lodes, and chlorine with the apatite lodes. The fluorine in this connection is accompanied by a little chlorine. The chlorine of the Norwegian apatite lodes occurs partly in chlor-apatite, but particularly in scapolite, which contains 2·5–3 per cent of chlorine. Scapolite is also found in considerable quantities in the altered country-rock. With the Canadian apatite lodes the chlorine is accompanied more or less by fluorine.

6. Chemically and mineralogically a remarkable analogy exists between both classes of lode and their respective country-rocks, in so far that in the granitic and granite-pegmatite dykes on the one hand several of the elements characteristic of cassiterite occur, while on the other hand the gabbro in which the apatite lodes occur is distinguished by richness in phosphoric acid, titanic acid, ferric oxide, ferro-magnesium and lime-soda silicates, and at the same time by a diminution of the potassium silicates. Almost all the elements which are distinctive of tin lodes, such as Si, Sn, F, B, P, Li, Be, U, Nb, Ta, Mo, W, are also highly characteristic of granitic and granite-pegmatite dykes, while in the case of the apatite lodes and gabbro the elements Si, Ti, Fe, Mg, Ca, Na, P, and Cl are distinctive. This chemical analogy between the lode material and the enclosing rock, taken in conjunction with the regular genetic dependence of the former upon the latter, leads to the conclusion that the lode material comes from the particular eruptive concerned. The extraction of this material however is not to be explained by some manner of segregation in the already consolidated rock, and the assumption remains therefore that this extraction proceeded during the magmatic condition of the eruptive. Moreover since the tin- and apatite lodes were formed immediately after the eruption of granite and gabbro respectively, and since at their formation halogen compounds were the active agents in the process, it follows that the extraction of the lode materials must be referable respectively to the action of hydrofluoric and hydrochloric acids, dissolved in the magma, or to fluorides and chlorides. Further, it appears reasonable to assume that SiF_4 must be formed in the granitic magma and that therewith on the one side acids with weak affinity for their bases, such as for instance stannic, tungstic, and uranic acids, would together with phosphorus and boron be extracted, and on the other side a strong base such as lithium. The assumption of an acid extraction taking place in the granitic magma explains at the same time the concentration of several of the elements particularly associated with tin. For the apatite lodes likewise it provides an explanation particularly of the concentration of the compounds of phosphorus and titanium.

In some parts of the world, as for instance in the Straits Settlements, Cornwall, the Erzgebirge, etc., granite is almost invariably accompanied by cassiterite, while in other granite districts that mineral is unknown. In the whole of the Scandinavian peninsula for instance, apart from some immaterial occurrences, no deposit of cassiterite is known, in spite of the enormous distribution of granite.

Allied to the tin lodes proper in the restricted sense of that term are the tin-copper lodes of Cornwall and of the Herberton district, Queensland, etc.; the tin-wolfram lodes of several localities; and the wolfram lodes

without tin. To this group belong also the cryolite deposits of Greenland and perhaps also some but little investigated apatite lodes in the granite of Zarzala in Spain. All such deposits as these, are to be regarded as pneumatolytic facies genetically closely connected.

Somewhat more distant genetically are the Alpine titanium lodes investigated formerly by Daubrée [1] and more recently particularly by E. Weinschenk.[2] According to the latter authority these are "characterized chiefly by the presence of a small amount of titanic acid, besides which in some of the occurrences, molybdenum, wolfram, and beryllium are also present; the principal gangue minerals of these lodes are quartz, felspar, apatite, and calcite. . . . On the one hand the firm conviction of a common dependence of these Alpine titanium lodes upon the granitic mass is obtained, though on the other hand it is plainly recognized that the formation of these titanium occurrences of the Central Alps may not off-hand be considered as the equivalents of the tin lodes, but between the two classes of deposit there exist fundamental differences based upon the manner of their formation."

Again, with the contact iron deposits tin lodes have this in common, that both represent the expiring stages of an eruption, such eruption being principally of granite. It must nevertheless be conceded that the chemistry of processes which have for result the formation of two distinct classes of deposit must have been fairly different, though the tourmalinization of many contact rocks, the appearance of axinite in some contact iron deposits, and the occasionally abundant occurrences of specularite and magnetite in some tin lodes, remain as distinct analogies between the two. As already stated [3] the deposit of Pitkäranta in Finland, and that of Schwarzenberg in the Erzgebirge, etc., may be regarded as connecting links between the tin lodes on the one side and the contact iron deposits on the other.

Between the tin lodes and the sulphide or lead-silver lodes the old French school essayed to draw an absolutely sharp line, some disciples of that school even going so far as to divide all lodes into two main divisions, the *filons stannifères*, the fumarolic products of granite; and the *filons sulphurés dites plombifères*, the deposits from thermal waters, these latter having been considered by some to be invariably connected with basic rocks. Just as this last statement is of a certainty not correct, so also, in view of such clear cases of transition as are found in Cornwall for instance, can no such sharp division as the above be maintained. In

[1] Résumé in *Études synthétiques*, 1879.

[2] 'Die Minerallagerstätten des Gross-Venediger Stockes; ein Beitrag zur Zenntnis der Alpinen Minerallagerstätten,' *Zeit. f. Kryst. u. Min.* XXVI., 1896.

[3] *Ante*, p. 352, 405–411.

that tin field many lodes carry approximately equal amounts of tin ore and of sulphide copper ore, the latter also being often accompanied by tourmaline, etc. Further, there are in Chili many copper lodes which, though they contain no tin, have this in common with the lodes of Cornwall, that they contain much tourmaline. At Telemarken in Norway also, sulphide copper lodes are known to have all the distinguishing marks of tin lodes, to contain mica, tourmaline, fluorite, etc., to be connected with granite, and to be marked by an alteration of the country-rock something in the nature of greisen formation, yet to contain no tin, the place of this being taken by copper. Further, in the Erzgebirge as well as in Cornwall many connecting links may be observed between the tin lodes or tin-copper lodes on the one hand and the ordinary lead-silver lodes on the other. The silver-tin lodes of Bolivia described by A. W. Stelzner are in this connection particularly pertinent.

The *filons stannifères* and the *filons plombifères* are it is thus seen connected with one another by certain transition or intermediate members. That this is so however does not remove the extremely sharp and remarkable differences between representative types of the two classes. Though cassiterite for instance is found with much stannite in the Bolivian lodes and as microscopic crystals in the sphalerite of the pyritic lead lodes of Freiberg, and though similarly the sulphide lead lodes in the neighbourhood of Argelèze Gazost in the North Pyrenees near the surface carry galena with cassiterite, such occurrences do not however alter the fact that the association of tin with sulphide lead-zinc ores is a rare occurrence.

Apatite so characteristic of the tin lodes is just as little observed in the sulphide-gold and lead-silver-zinc lodes as is topaz. On the other hand another mineral typical of the tin lodes, wolframite, sometimes occurs in lead-silver lodes, as for example in association with fluorite near Neudorf in the Harz, and in some other geologically allied occurrences. Uranium ores are more often associated with cassiterite, yet the chief deposit of radium-bearing pitchblende, that at St. Joachimstal in the Erzgebirge, is connected not with cassiterite but with silver-bismuth-cobalt lodes, which lodes however, it must be admitted, are to be regarded as genetically connected with granite.

Generally speaking tin ore does not occur in massive but rather in fine veins and impregnation fractures, or distributed throughout a greisen zone. Upon weathering, the rocks in which these various deposits occur surrender their ore to form tin gravels. In such gravel-deposits all those chemically resistant minerals collect which at the same time possess high specific gravity and the necessary hardness, and accordingly cassiterite, quartz, tourmaline, zircon, wolframite, etc., are found together. Felspar on the other hand disintegrates to a clay which together

with mica is washed away. Another economically important result of weathering is that the arsenopyrite, which often occurs plentifully in the primary deposit, and the sulphides of copper, bismuth, etc., in consequence of their decomposition, are not found in the tin gravels, the concentrate from which yields accordingly a very pure metal.

In the time of the Phœmicians, Greeks, and Romans, the tin gravels of Cornwall, Galicia in Spain, and Lutitavier in Portugal, played an important part, though all are now practically exhausted. On the other hand the tin production of Australia to-day includes much which is derived from gravels, while in the Straits Settlements, including the East Indies generally, the tin ore won is almost entirely gravel-tin. It may indeed be reckoned that at present about three-quarters of the world's annual production of tin is derived from gravel-deposits, chiefly those of the Straits, and but one-quarter from lode-tin, this being chiefly from the tin-silver lodes of Bolivia and the tin lodes of Cornwall and Australia.

Figures of the tin production of the world are given in the following table wherein those for Bolivia are the calculated contents of the exported ore.

	1825.	1850.	1875.	1890.	1900.	1908.
England	4428	6,837	9,771	9,752	4,336	4,500
Saxony	140	94	85	64	?	?
Bohemia	40	45	160	49	40	?
Finland	... [1]	... [1]	... [1]	13	4	...
France, Spain, Portugal	... [2]	... [2]	... [2]	... [2]	... [2]	... [2]
Banka-Billiton	1188	3,184	8,130	10,718	17,922	} 77,000
Straits Settlements	...	...	8,703	27,910	47,310	
Japan	...	...	...	48	12	...
Australia	...	...	7,325	6,518	3,800	6,400
Bolivia	...	...	...	1,691	10,245	*ca.*18,000
Total tons	5800	10,200	35,000	57,000	85,000	106,000

[1] Trifling amounts. [2] In some years trifling amounts.

To these figures must be added the local consumption in the Straits and neighbouring countries, the production of China, and the small production of Mexico, the last being at the most 50 tons. Other statistics have already been given.[1]

The ore hoisted from the richest of the tin mines in Cornwall generally yields 2·5–3 per cent of cassiterite or approximately 1·75–2 per cent of metallic tin, though the majority of the mines only produce ore containing 0·7–1·5 per cent of tin. Those of the Erzgebirge, when formerly working, delivered ore with 0·2–0·5 per cent.

[1] *Ante*, pp. 207, 208.

The Saxon-Bohemian Erzgebirge

LITERATURE

B. von Cotta. Die Lehre von den Erzlagerstätten, 1861, Vol. II.—H. Müller. 'Bildung der Zinnstockwerke,' B. u. H. Ztg., 1865, p. 178.—E. Reyer. 'Zinnerzführende Tiefeneruptionen von Altenberg und Zinnwald,' Jahrb. d. k. k. geol. Reichsanst., 1878; Geologie des Zinnes, 1881.—A. W. Stelzner. 'Die Granite von Geyer und Ehrenfriedersdorf, sowie die Zinnerzlagerstätten von Geyer,' Beitr. z. geogn. Kenntn. d. Erzgeb., I., Freiberg, 1865.—R. Beck. 'Einige Beobachtungen im Gebiete der Altenberg-Zinnwalder Zinnerzlagerstätten,' Zeit. f. prakt. Geol., 1896, p. 148.—K. Dalmer. 'Der Altenberg-Graupener Zinnerzlagerstätten distrikt,' Zeit. f. prakt. Geol., 1894, p. 313; ibid., 1895, p. 228; 1896, p. 1; 1897, p. 265.

Explanatory texts to the geological map of Saxony with drawings of ore-deposits, in part by H. Müller; sections Eibenstock, 1884, and Falkenstein, 1885, by Schröder; sections Johanngeorgenstadt, 1885, Dippoldiswalde-Frauenstein, 1887, and Glashütte-Dippoldiswalde, 1888, by Schalch; sections Auerbach-Lengefeld, 1885, and Altenberg-Zinnwald, 1890, by Dalmer.

The Saxon-Bohemian granite, as illustrated in Fig. 266, is chiefly arranged in two occurrences which, extending north and south, interrupt the gneiss-phyllite formation of the Erzgebirge. Of these two occurrences the westerly extends from Carlsbad in Bohemia to near Schneeberg in Saxony; and the easterly from Teplitz through Altenberg-Zinnwald to Dippoldiswalde or thereabouts, throughout which extent it is accompanied by acid porphyries of Permo-Carboniferous age.

With this granite the Erzgebirge tin occurrences are most closely connected. The deposits are distributed as follows: in the eastern area, at Graupen in Bohemia, Zinnwald on the frontier between Saxony and Bohemia, at Altenberg and several places near Glashütte and Dippoldiswalde; in the western area, at Schlackenwald, Platten, Johanngeorgenstadt, and at Eibenstock in Saxony; east of this again, yet in the neighbourhood, at Geyer, Greifenstein, and Ehrenfriedersdorf; while Marienberg and Seiffen are fairly isolated occurrences about midway between the two granite areas.

Generally speaking, in the district which includes Graupen, Zinnwald, and Altenberg, three eruptive rocks present themselves for consideration, these being the Teplitz quartz-porphyry, which is the oldest, then granite-porphyry, and finally the stanniferous granite, this being the youngest.

Form of the Deposits.—For quite a number of these occurrences stockworks are characteristic. With this type of deposit not only the granite but also the adjacent country-rock is usually so traversed by veins and impregnated, that the whole mass must be mined. This at Altenberg is 900 m. long and of an equal width. In other places, as for example at Zinnwald where the granite has actually broken through the Teplitz porphyry, the ore, as illustrated in Fig. 265, occurs as lode-like floors, *Flöze*, following the flat jointing of the granite. These flat lodes do not

run quite parallel to the granite outline, but bending upwards like a basin or a watch-glass, they pass out into the country-rock. The lode

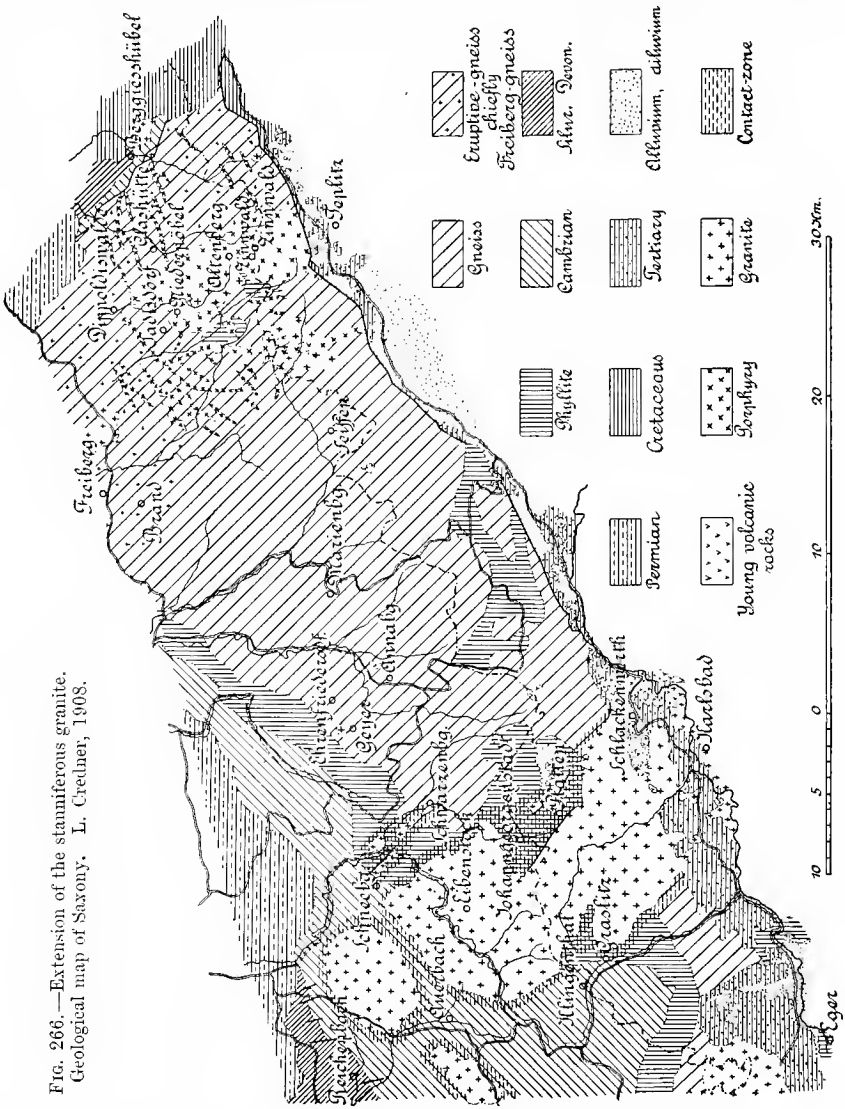

Fig. 266.—Extension of the stanniferous granite. Geological map of Saxony. L. Creduer, 1908.

material, which may be 2 m. in width, as illustrated in Figs. 117 and 146, usually exhibits a well-defined and often symmetrical structure. Of the different minerals present, mentioning only those of any importance, lithia-mica is the oldest, following which come wolframite, quartz, cassiterite,

and then scheelite, the youngest of all. It is usually the case however that more than one generation of quartz and cassiterite may be distinguished. A third type of deposit is represented by the steeply inclined lodes, which when they occur in the quartz-porphyry, as they often do, are occasionally crossed by dykes of a close-grained granitic rock. At Geyer and elsewhere a pegmatitic granite of very coarse grain, occurring between the ordinary granite and the country-rock, and consisting of innumerable segregations chiefly of quartz or felspar, is under favourable conditions worked for these minerals. The felspar in some places is so decomposed that the resultant kaolin is worked.

As pointed out by Dalmer particularly, the tin-deposits in the Erzgebirge occur most frequently in the upper portions of the granite and in the mantle of country-rock, while deeper into the central portion of the granite they are either sparingly present or are entirely absent ; at Altenberg for example the ore continues to a depth of 230 m., below which it is no longer worth working. The deposits are not limited to the granite and porphyry but occur also in the surrounding slate. The tin lodes for instance at Sauberg near Ehrenfriedersdorf north-east of Geyer, are found in bands, so-called *Risse*, in mica-schist, with beautiful crystals of cassiterite, apatite, etc. Under analogous conditions lodes occur in the contact aureole of the large Eibenstock granite mass and also near Schlaggenwald, while the deposits at Graupen, stated to have been worked since the twelfth century, lie partly in gneiss and partly in quartz-porphyry.

From the occurrence of the tin lodes in the upper portions of the granite, and from the fact of their intersection in places by younger granitic dykes, it must be concluded that the bulk of the vapour emanations were given off in the early stages of the granite eruption and were thus enabled to develop their mineral-building activity in the portions of the granite already consolidated as well as in the country-rock, under conditions of contact-metamorphism.

The occurrences of tin ore in the Erzgebirge and in Cornwall have provided the material for the geological and genetic investigation of tin lodes in general. At those places began also the mineralogical study of tin lodes and of the group of tin minerals, many of which are so characteristically developed ; for instance the knee-shaped crystals of Saxony, *Visiergraupen*, the zinnwaldite of Zinnwald illustrated in Fig. 117, the apatite of Ehrenfriedersdorf, the topaz of Schneckenstein, and the topazified granite of Geyer and of Zinnwald-Altenberg.

The Erzgebirge tin lodes occasionally carry sulphide ores in addition, those at Sadisdorf and Seiffen for example which contain chalcopyrite. In the matter of their filling also they therefore resemble the tin lodes of

Cornwall. Since it can be shown that the lead-silver-zinc lodes in their upper levels also carry some tin there exists in this district no sharp demarcation between the tin lodes and those of lead-silver-zinc.

The content of these Saxon tin-deposits like that of all other tin districts is low. At Altenberg the lodes contain 0·1–0·9 per cent of cassiterite, and the zwitter 0·3 per cent of metallic tin. The lodes of the Saxon-

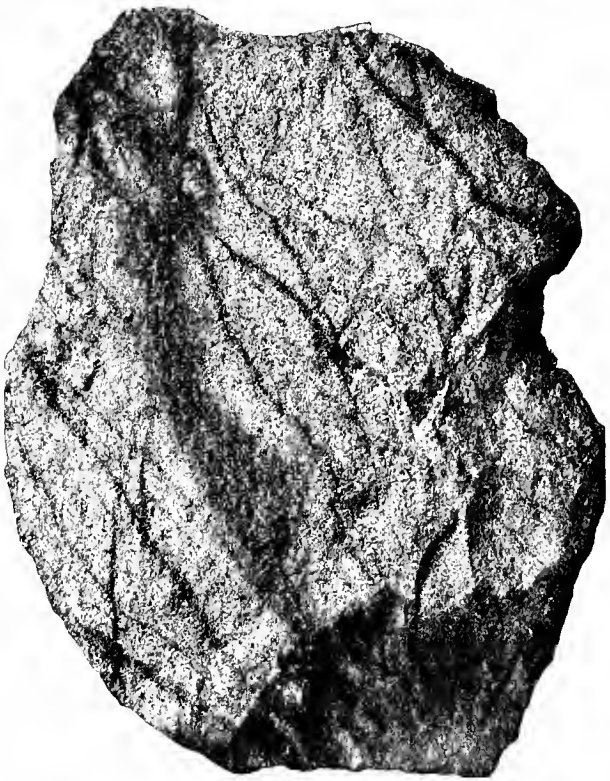

Fig. 267.—Cassiterite veins and greisen in the Altenberg granite.

Bohemian Zinnwald contain 0·2–0·8 per cent of tin and 1–2 per cent of wolframite ; the greisen with 0·2–0·5 per cent of tin is poor in wolframite.

The early beginnings of tin mining in Saxony date back in the case of Graupen to the end of the twelfth century; from this neighbourhood about 50 tons of zwitter are still obtained annually. Altenberg, discovered in the year 1458, produced in its early days as much as 300 tons annually, though the production for 1907, representative of the scale of operations to-day, was only 16·8 tons. It is probable however that, as with many tin districts, the early production at this place also, was derived from its

eluvial deposits, the situation of which relative to the lodes is indicated in Fig. 5. Zinnwald, where work was also begun in the fifteenth century, reached its zenith of production in the middle of the sixteenth, while to-day mining operations there are very limited. The relatively large amount of wolfram present was in 1898 responsible for a moderate revival to the extent that in that year 50·5 tons of wolframite, 116·8 tons of lithia-

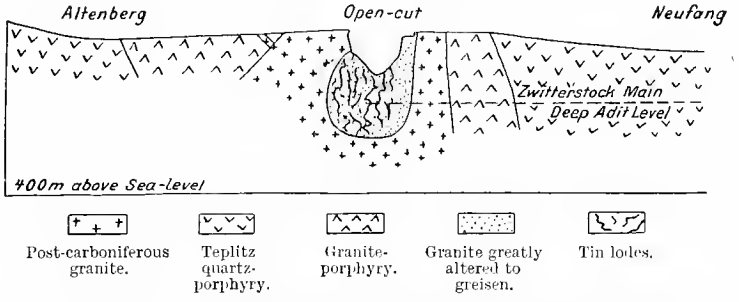

Fig. 268.—Section along an easterly line at Altenberg. *Blatt Zinnwald, der geol. Spezialkarte von Sachsen.*

mica for firework purposes, and 1·2 tons of cassiterite were produced. Bohemian Zinnwald in 1906 produced 49·9 tons of wolframite; Saxon Zinnwald in 1907, 59 tons of wolframite and stanniferous wolfram ores, and 1·2 tons of cassiterite. At Geyer, mining, which began in the year 1315, has now practically ceased, only a few tons of tin ore being produced yearly. This is also the case at Ehrensfriedersdorf. The wolframite and molybdenite mines of Niederpöbel near Sadisdorf in 1907 yielded 3·05 tons of wolfram ore and 1·2 tons of molybdenite.

Fichtelgebirge

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R. Beck. Erläuterungen zur Sektion Elster-Schönberg der geologischen Spezialkarte von Sachsen, p. 23.—v. Gümbel. Fichtelgebirge, 1879.—A. Schmidt. 'Mineralien aus den auflässigen Bergwerken des Fichtelgebirges,' Wunsiedeler Ausst., p. 9.—Machert. 'Über Zinnbergbau im Fichtelgebirge,' Inaug. Diss., Erlangen, 1894.

In the granite masses of the Fichtelgebirge and in the surrounding contact-zones tin lodes occur which in olden times were worked. The best known of these is that at Weissenstadt. Beck examined the stanniferous lodes of Wernersreuth which traverse the gneiss on the Zinnberg.

France

LITERATURE UPON LA VILLEDER

Lodin. 'Note sur la constitution des gîtes stannifères de la Villeder (Morbihan),' Bull. Soc. Géol. 3e Sér. Vol. XII. p. 645, 1883–1884.—Baudot. 'Les Mines d'étain de la Villeder (Morbihan),' Bull. Soc. Ind. min. de Saint-Étienne, 3e Sér. Vol. I. p. 151, 1887.

Tin deposits of the Saxon type are found in the Brittany granite near La Villeder, department Morbihan. Here a granite mass, which towards the west extends to Baud and Lorminé, is enveloped in Cambrian sandstones and slates contact-metamorphically altered by the intrusion of the granite, one consequence of this intrusion being that both granite and slate in the neighbourhood of their contact are traversed by veins of cassiterite, much as in stockworks. The principal material of these veins is quartz, which is accompanied by cassiterite, apatite, fluorite, molybdenite, arsenopyrite, pyrite, sphalerite, chalcopyrite, galena, etc. Topaz and tourmaline occur but seldom, while wolframite is entirely absent. Mineralogically, this occurrence is rendered particularly interesting by the appearance of phenakite, the beryllium silicate; economically it is without significance.

At Tyriac, west of the mouth of the Loire, tin lodes also occur. On the Central Plateau the following discoveries of tin ore of the Saxon type are worthy of mention: at Montebras, numerous veins;[1] at Cieux, a lode almost 1 m. wide; at Vaulry, stockworks, etc. The veins of Montebras according to Vogt[2] are worked for amblygonite, the lithium phosphate.

Spain and Portugal

The deposits in this corner of Europe occur along a north-west line extending from Zamora north of Salamanca, through the north-eastern portion of Portugal to the province of Orense in Galicia. The principal discoveries[3] lie in the eastern portion of the province Orense, at Penuta and Romilo, between Verin and Monterey, on the Portuguese boundary, among the Montesund Avion hills, and near Pontevedra. The lodes here occur in crystalline schists near a granite contact, being occasionally, as at Viana del Bollo, very rich. The continuation into Portugal appears in the province of Beira Alta at Vizeu, and in that of Traz os Montes, at Montesinhos, Parada, Coelhoso, Marao Angueira, Valle Seixo, etc. The lodes reach 0·5 m. in thickness, and occur sometimes in gneiss and sometimes in decomposed pegmatitic granite.

[1] De Launay, *Traité des gîtes minéraux*. Vol. II. p. 142.

[2] *Trans. Amer. Inst. Min. Eng.*, Richmond Meeting, 1901, p. 11.

[3] J. Ahlburg, 'Die nutzbaren Mineralien Spaniens und Portugals,' *Zeit. f. prakt. Geol.*, 1907, p. 183.

Other tin deposits in the Iberian Peninsula occur at Terrubias and Santo Tomé de Rozadas near Salamanca, at San Isodoro and Marinera near Cartagena, near Almeria on the south coast of Spain, and near Ramalhoso in the neighbourhood of Amarank in Portugal. The gravel-deposits of Spain and Portugal were worked by the Romans and Phœnicians. Some idea of the present production is afforded by figures of 47 tons and 209 tons for Spain during the years 1900 and 1905 respectively, and 81 tons and 31 tons for Portugal during the years 1900 and 1901.

Some of the lodes are rich in wolframite, and wolfram mining in consequence appears at the moment to be developing more favourably. This ore however occurs not only with the tin lodes but also in special wolframite lodes. The best-known wolframite occurrences are those at San Finx in the province of Galicia, and at Montaro in Cordoba, but others are also known in the provinces Caceres, Salamanca, Orense, and Pontevedra. In 1905 San Finx produced 400–450 tons, Salamanca about 100 tons from gravel-deposits, Pontevedra about 200 tons, Cordoba about 100 tons, and Caceres 25–35 tons. The total production from Spain varies extremely; while for 1900 it was 1958 tons, in 1901 it was only 6 tons, though in 1905 again it had risen to 900 tons. The Portuguese output of wolframite is low; in 1901 it was 90 tons.

Cornwall

LITERATURE

H. T. de la Bêche. Report on the Geology of Cornwall, Devon, and West Somerset, 1839.—W. J. Henwood. 'On the Metalliferous Deposits of Cornwall,' Trans. Roy. Geol. Soc., Cornwall, V., 1843, and other papers; Presidential Address, Roy. Inst., Cornwall, 1871.—L. Moissenet. Ann. des Mines. Paris, 5e Sér., XIV., 1858; XV., 1859; 6e Sér., II., 1862. Observations on the rich parts of the Lodes of Cornwall. Truro, 1877.—C. le Neve Foster. Papers, Trans. Geol. Soc. Cornwall, 1875, 1876, 1877, 1878; Miners' Assoc. Cornwall and Devon, 1866, 1875; Quart. Journ., 1875, 1878.—J. H. Collins. Various papers. Handbook to the Mineralogy of Cornwall and Devon. Truro, 1876. 'On the Origin and Development of Ore Deposits in the West of England,' in five parts, Journ. Roy. Inst. Cornwall, 1890, 1892, 1893, 1895, and 1897.—Reyer. 'Zinn,' 1881.—R. Hunt. British Mining, 1887.—J. A. Phillips and H. Louis. A Treatise on Ore Deposits, 1896, pp. 191-240.—J. B. Scrivenor. 'The Granite and Greisen of Crigga Head, Western Cornwall,' Quart. Journ. LIX., 1903.—The Memoirs of the Geol. Survey of England; Geology of (1) The Land's End District; (2) Of Camborne and Redruth; (3) Of Newquay; (4) Of Plymouth and Liskeard; all of recent years, and others in preparation.—D. A. MacAlister. 'Geol. Aspect of the Lodes of Cornwall,' Econ. Geol. III., 1908.

The Cornish peninsula, including the adjoining portion of Devonshire, is occupied in greater part by Palæozoic strata, represented chiefly by Devonian and to a less extent by Cambrian, Silurian or Ordovician, and Culm, the distribution of these being as given in Fig. 269. Among these strata, clay slates, in places much contorted, and known locally as 'killas,' are widely distributed, while with them the serpentine of the Lizard, as well

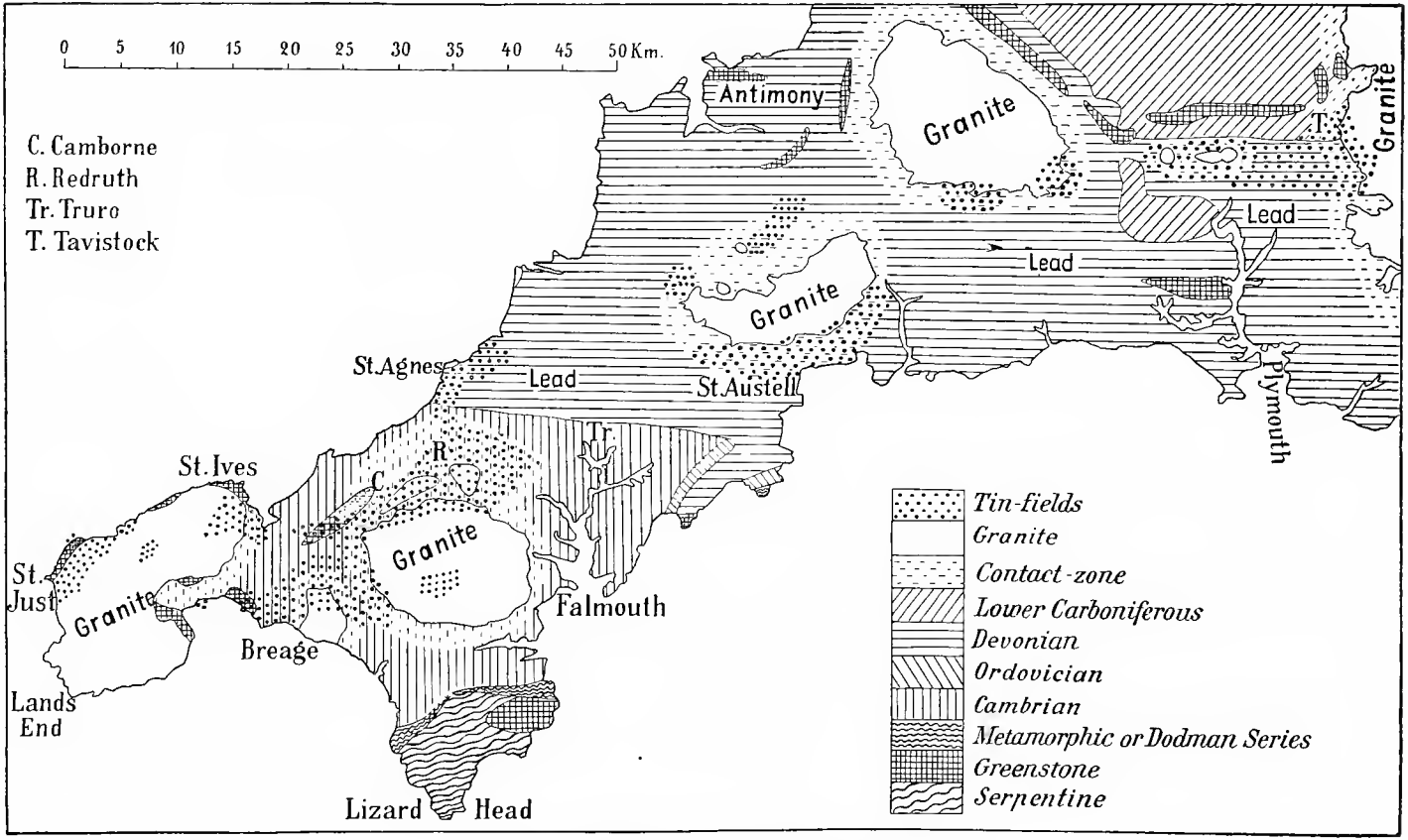

FIG. 269.—Geological map of the West of England. MacAlister.

as some gabbros, greenstones, etc., must also be reckoned. These ancient formations are intruded by five larger and several smaller roundish granite bosses which, when the occurrence in the Scilly Islands to the south-west is included, form an east-north-east line about 220 km. long. These doubtless all belong to one connected occurrence beneath, from whence their eruption took place in late Carboniferous or post-Carboniferous time. The several masses, which as illustrated in Fig. 163 generally extend in depth at a low angle, determine in greater part the relief of the country and the configuration of the peninsula, while their effect upon the surrounding strata has been to produce pronounced contact-metamorphism.

From these as centres, numerous apophyses locally known as ' elvans ' proceed, these consisting chiefly of quartz- or felsite-porphyry of the same composition as the granite.[1] Such elvans vary in thickness from 1 m. to 100 m. or perhaps even more, while along the strike they may occasionally be followed for 20 km. Their general direction is usually east-north-east, that is more or less in agreement with the strike of the slates and parallel with the line of the granite masses. Around the margins of these latter the tin and copper lodes occur, partly within the granite itself and partly within such slates as have suffered contact-metamorphism and are freely traversed by elvan dykes. As may be gathered from Fig. 269, it is seldom that such lodes are found more than 3 km. from the granite contact. Since in depth the granite masses underlie the slates, it often happens, as illustrated in Figs. 163 and 270, that mines which at the surface were started in slate, in depth enter the granite.

The tin- and copper ores are found partly along the joint-planes of the granite, forming impregnation fractures, stockworks, etc., or they occur in proper tectonic lodes up to several metres in thickness, these being often characterized by a brecciated structure. The principal ores are: cassiterite, with some stannite; chalcopyrite, bornite, and chalcocite; arsenopyrite and other arsenic minerals; wolframite and scheelite. Less important are tetrahedrite, silver ore, sphalerite, bismuthinite, cobalt- and nickel ores, pitchblende, manganese ore, different iron ores, the phosphate, arsenate, and carbonate of lead, etc. The last-named, together with the oxides, carbonates, and silicates of copper, native copper, and some sulphide copper ores, are secondary products belonging partly to the oxidation and partly to the cementation zones.

The most important gangue minerals are quartz, chlorite, tourmaline, fluorite, and kaolin. The abundance of tourmaline and the frequent tourmalinization of the country-rock, whether that be granite or slate, are remarkable features of these lodes. Where the walls are of calcareous hornstone the tourmaline is replaced by the lime-boron silicate, axinite;

[1] J. A. Phillips, *Quart. Journ.*, 1875, p. 334.

the granite in the neighbourhood is also often kaolinized; topaz on the other hand does not often occur.

The lodes of Cornwall afford typical examples of lode-relations of all kinds; of intersection often accompanied by rich ore; of junction; deflection; drag; displacement; etc. From observation of the effect of these relations it was endeavoured at one time to construct laws defining the ore distribution, particularly in relation to the strike. Moissenet even went so far as to treat the question mathematically, without however arriving at any definite result.

Tin- and copper ores occur sometimes intimately associated in the same lodes. In such cases near the surface the copper of the original sulphide ores has been removed and in greater part deposited as secondary ore in the cementation zone. The cassiterite under the same circumstances suffers no migration and it therefore results that such lodes in their upper levels are particularly worked for tin. Cornwall however not only offers good examples of secondary depth-zones but is remarkable also for its striking primary zones. Copper ores prevail in the comparatively shallow levels, while those of tin only occur to any extent in greater depth. In the case of Dolcoath, the most productive and at the same time the deepest mine in the district, copper ores almost exclusively were worked to a depth of roughly 300 m. Below this there followed a zone in which both metals were well represented; while deeper still, to the present depth of about 950 m., tin ore occurs almost exclusively. As will be seen from the stoping plan given in Fig. 270, work at this mine first began in the slate, the granite only appearing in depth. The boundary between these two rocks coincides approximately, though far from exactly, with that between the areas worked respectively for copper and tin. Similar primary depth-zones have been observed in several other mines.

Besides these tin-copper lodes wherein the amount of galena is unimportant, lead-silver lodes are also found in the slates, though at greater distance from the granite. These strike approximately north-south or roughly at right angles to the slates and represent a later formation, presumably of Tertiary age. In other respects also they are quite distinct from the tin-copper lodes and are therefore not to be regarded as pneumatolytic or pneumatohydatogenetic effects in connection with the granite intrusions.

Not many decades ago 180 mines were at work in this West of England region, 9 in the neighbourhood of Tavistock in Devonshire, and the remainder in Cornwall, more especially around the two western granite masses. Since 1890 however the scale of operations has considerably contracted and in 1896 there were but 17 mines producing as much as or more than 100 tons of ore yearly. The most important tin mines include those

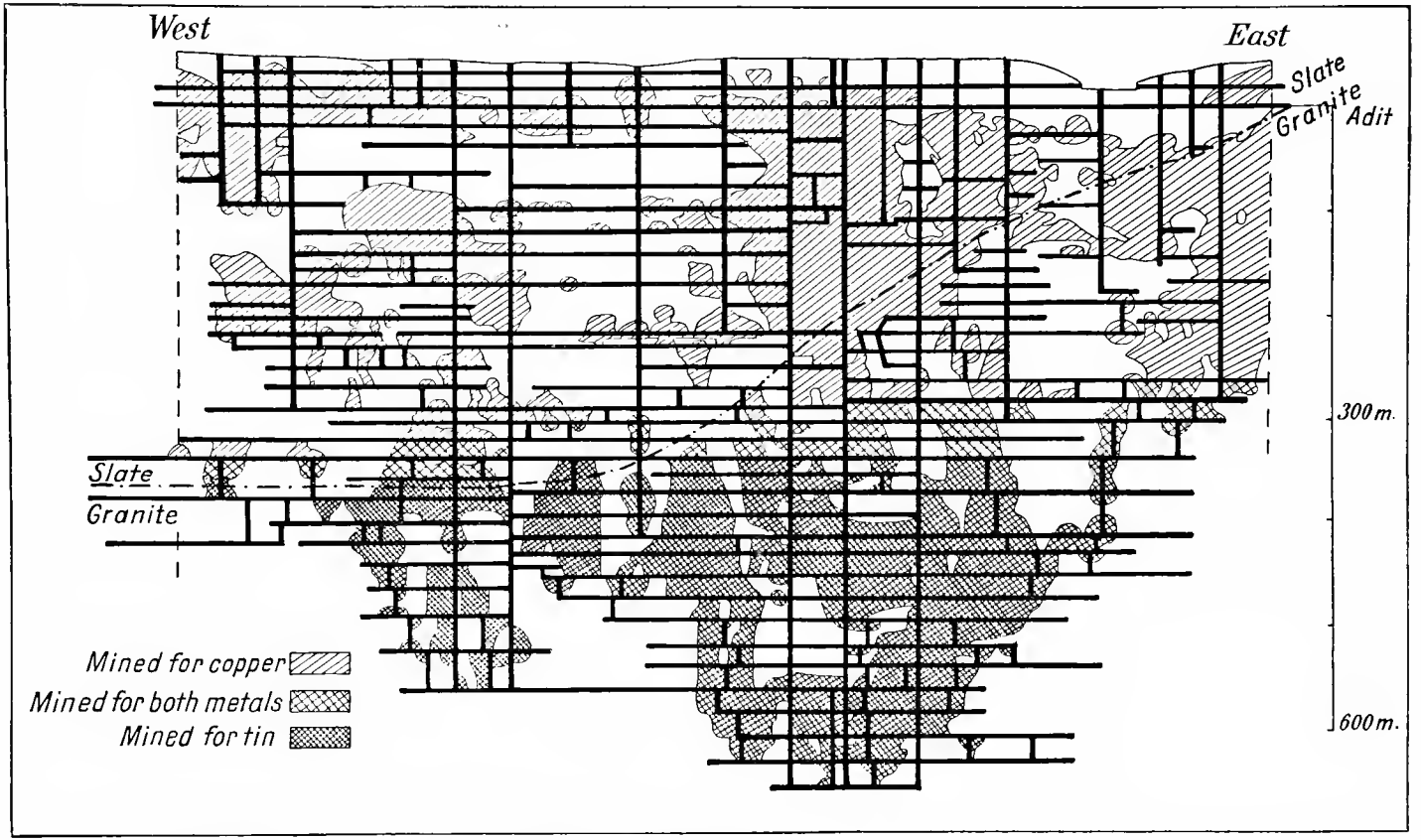

FIG. 270.—Longitudinal section of the Main Lode, Dolcoath. Neve Foster.

of St. Just, to the extreme west, where some of the lodes, as indicated in Fig. 162, are being worked under the sea; those of St. Ives also to the west; and those at Camborne and Redruth situated somewhat more towards the east. Among the latter are Dolcoath, Carn Brea, Tincroft, and Cook's Kitchen. The mines at St. Austell are centred around the third granite area farther to the east.

Those mines which formerly were the most important copper mines are found in the neighbourhood of Redruth, Gwennap, and St. Agnes. The uranium mine near Grampound on the third granite area works only for uranium ore, of which it produces about 20–30 tons annually.

In ancient times the gravel-tin deposits of Cornwall and Devon were very important. Work was continued upon these right through the Middle Ages and up to the commencement of the last century.

The total production of this mining region in copper and tin may be gathered from the following figures:

Total Tin Production.

1201–1749	about 712,000 tons.
1750–1905	„ 755,000 „

Gravel Tin Production.

1201–1600	about 75,000 tons.
1601–1800	„ 473,000 „

Total Copper Production.

1501–1725	about 20,000 tons.
1726–1905	„ 883,000 „

PRODUCTION IN RECENT YEARS

	Tons of Tin yearly.	Tons of Copper yearly.
1820–1840	3,500– 6,500	10,000–15,000
1850–1859	6,000– 7,000	15,000–20,000
1860–1869	8,000–10,000	10,000–15,000
1870–1879	9,000–10,500	3,500– 8,000
1880	9064	3600
1885	9484	2750
1890	9752	900
1895	6755	600
1900	4336	700
1905	4538	500
1908	4500	700

The considerable decrease in the amount of copper recently produced has resulted in part from the passage of some of the most important mines out of the copper zone into the deeper tin zone, and in part from the cessation of work on many mines worked for copper. The total production of the lead-silver mines from 1848 to 1884 amounted to 63,600 tons of lead and 90 tons of silver. These mines have now long been stopped.

The Straits Settlements including Banka, Billiton, etc.

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The Malay Peninsula and the islands of Banka and Billiton, consisting in greater part of granite, form together the most important tin region

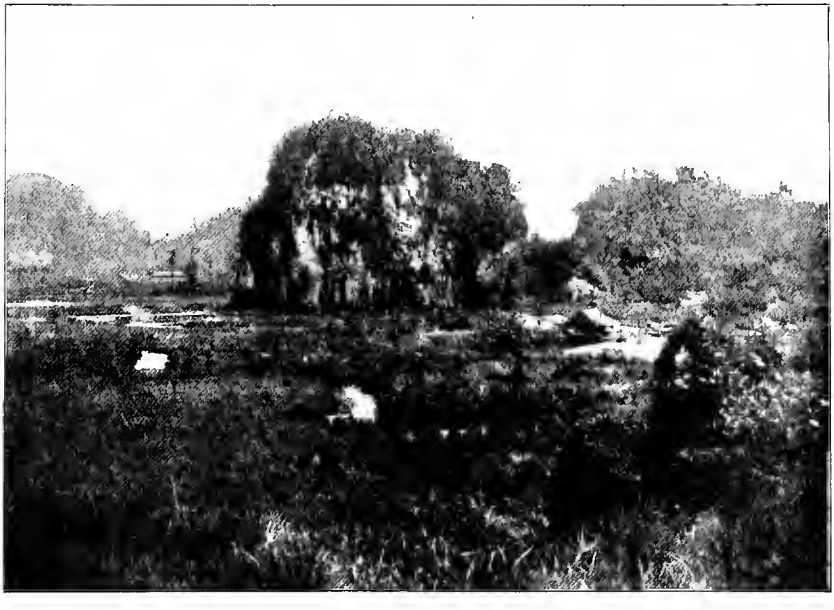
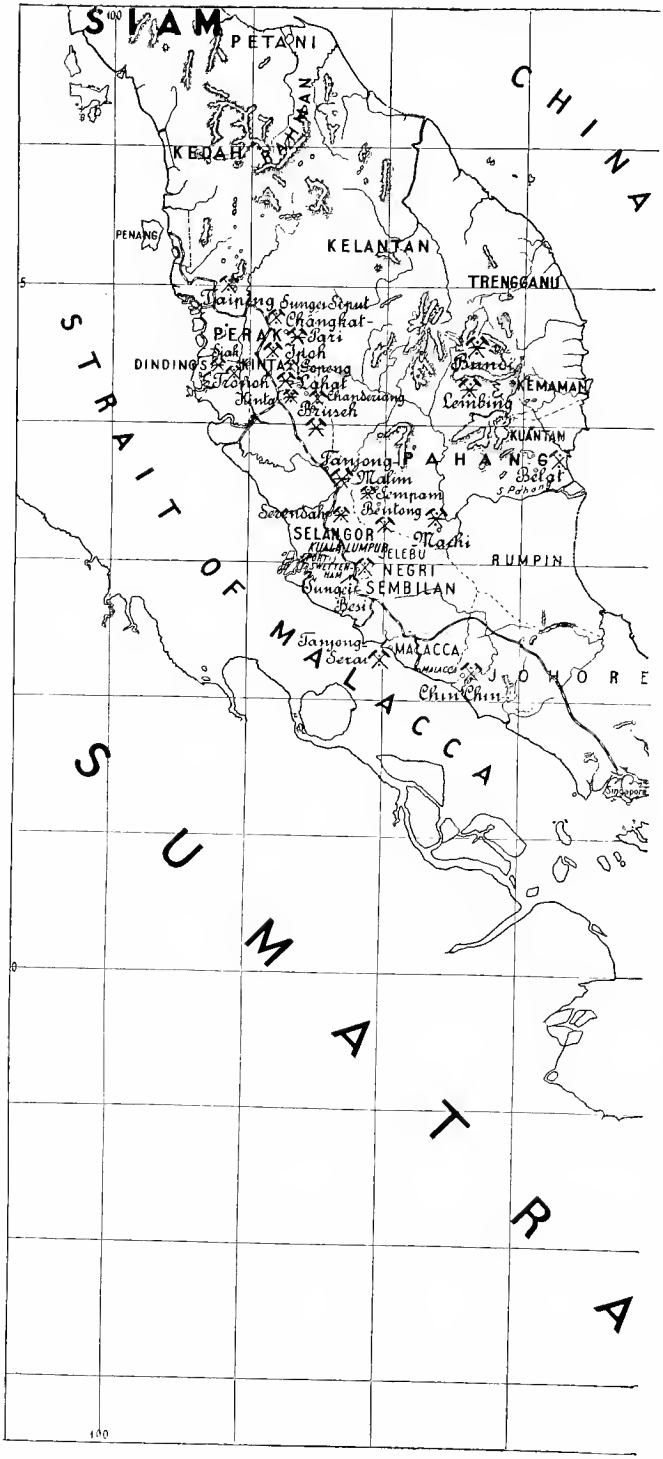


Fig. 271.—Landscape at Sungei Raia in Perak; showing precipitous limestone masses rising out of alluvial deposits in which to the right a gravel mine is being worked. Granite hills in the distance. Wolff.

of the whole world. The cassiterite here is almost exclusively won from gravel-deposits although there are mines working primary deposits. Some idea of the disposition of these gravel-deposits in regard to the present surface is afforded by Figs. 271 and 274, kindly supplied by Dr. Wolff. Mining in these countries takes rather the form of large and often deep excavations


SIAM
PETANI
CHINA
KEDAH
PATANI
PENANG
KELANTAN
TRENGGANU
Taiping
Sungei Siput
Changkat-Pari
PERAK
Ipoh
Siak
DINDINGS
KINTA
Gopeng
Tronoh
Lahat
Kinta
Chanderiang
Brusch
Bundi
KEMAMAN
Lembing
KUANTAN
Tanjong-PAHANG
Malim
Belat
S. Pahang
Sempam
Serendah
Bentong
SELANGOR
Machi
KUALA LUMPUR
ELEBU
RUMPIN
PORT SWETTENHAM
NEGRI SEMBILAN
Sungei Besi
Tanjong Serai
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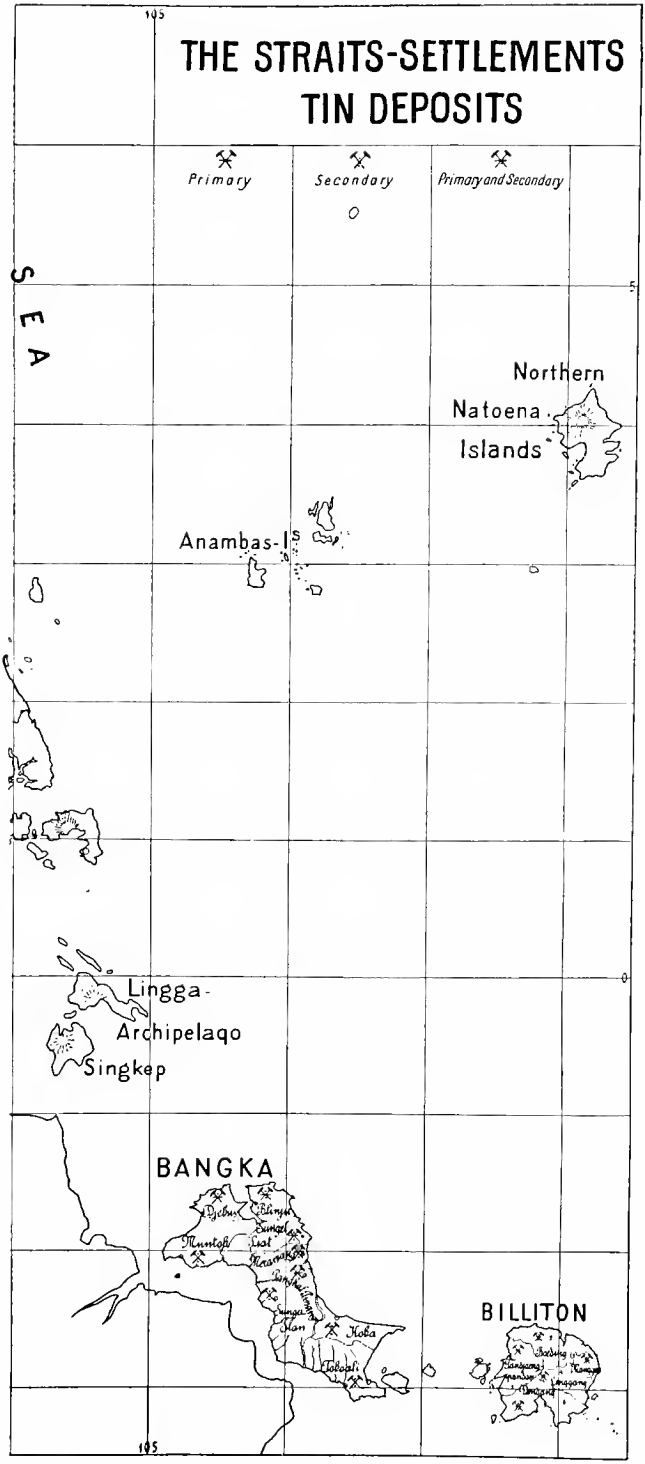
THE STRAITS-SETTLEMENTS
TIN DEPOSITS
Primary
Secondary
Primary and Secondary
SEA
Northern
Natoena
Islands
Anambas-Is
Lingga-
Archipelago
Singkep
BANGKA
BILLITON
105
5
0
105

than that of systematically planned mines. Louis however in 1899 mentioned a mine proper, 105 m. deep, in north-east Pahang.

According to Warnford-Lock and Scrivenor the different deposits are variously primary and secondary. Cassiterite occurs as a primary constituent of the granite though nowhere has it by differentiation been

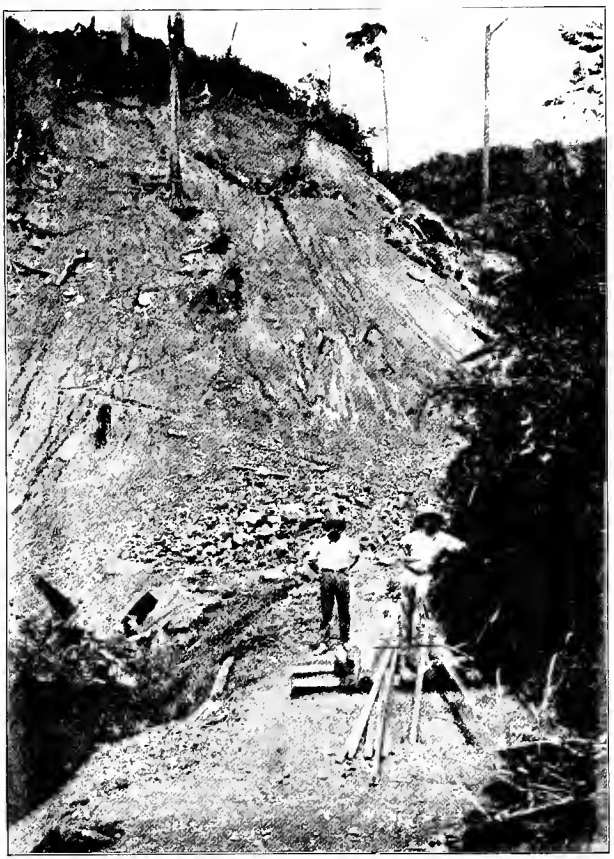

Fig. 273.—Opencut of the Rahman Tin Co., near Intan, Perak, showing wide shattered lode in slate.

concentrated sufficiently to form a payable deposit. The more important primary deposits occur when small veins containing cassiterite are so numerous as to constitute a stockwork. Such occurrences are found associated with greisen in the granite. In addition to cassiterite these veins contain quartz, mica, tourmaline, etc. Tin lodes have not yet been found in the surrounding slates though the chance of eventual discovery is decidedly good. Tin-bearing pegmatite is not unusual. At Bruseh and

Meru in the neighbourhood of Ipoh in Perak, such material is exploited. The association there of cassiterite with ferric oxide is particularly interesting, in that this oxide is probably the oxidation product of a sulphide existing in depth. The appearance of much tourmaline is from experience often taken to indicate greater richness in cassiterite.

In addition to their occurrence in granite, tin lodes also occur in limestone. The mine worked by Foo Choo Choon near Siak in the neighbourhood of Batu Gajah exploits such a lode. In that wide lode, which often shows

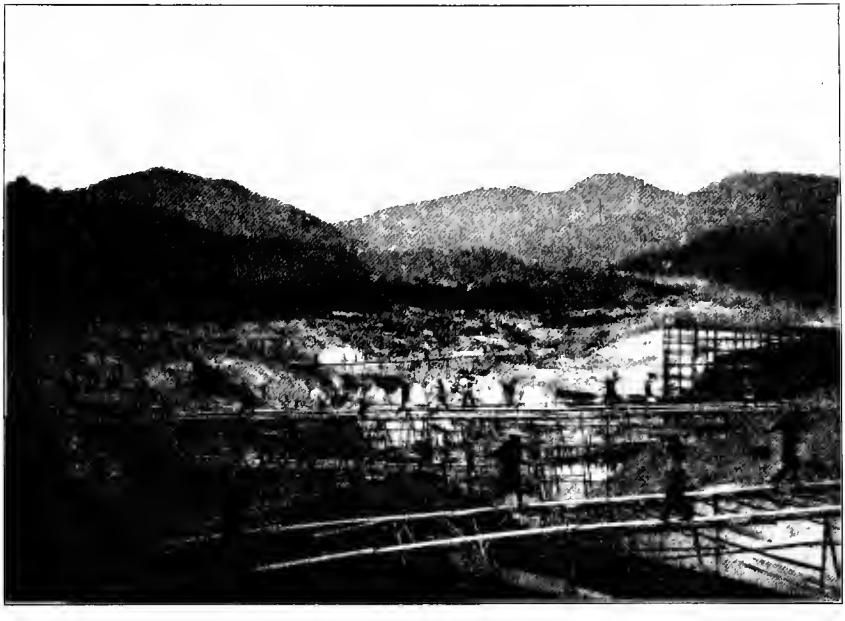

FIG. 274.—Opencut workings at Jelapang, near Ipoh, Perak. Gravel-deposit upon limestone. Granite hills in the distance. Wolff.

crusted structure, crystals of cassiterite up to one-quarter of an inch in length occur in quartz, together with arsenopyrite and other sulphides, though tourmaline appears to be absent. At Changkat Parit, in a similar lode, the cassiterite is accompanied by a large amount of pyrite, arsenopyrite, and rich copper sulphides. Outside of the Straits the occurrence of tin lodes in limestone has only so far been definitely established at Campiglia Marittima in Tuscany.[1]

The association of sulphides and cassiterite has this importance, that in this regard the primary deposits in the Malay Peninsula occupy a position intermediate between the Saxon type on the one side and the Cornish type

[1] *Ante*, pp. 409–411.

on the other. Further, the association of cassiterite with limestone and marble indicates a relationship of the tin-deposits with contact-metamorphic deposits.

The extensive gravel-deposits are not entirely alluvial but include some which are eluvial, while in addition deep pocket-fillings in the limestone are worthy of notice. These latter have supposedly been formed when the limestone has been so removed by weathering that the overhanging deposits have broken into fragments which have then been carried by water into the pockets where now they are found with the clayey residuum of

Fig. 275.—Hydraulicking at the Gopeng tin mine, Perak. Wolff.

the limestone and other rubble. In these pockets the association of cassiterite with newly formed pyrite is interesting.

These gravel-deposits are in greater part of Quaternary age. Their great extent is chiefly owing to the intense denudation suffered in the tropics. In sinking to them from the surface, the overburden, consisting of the unpayable beds of sand and clay, has first to be passed. This at Billiton is 4–6 m. thick; at Banka 8–12 m. or even at times 16 m. Below this, and generally directly upon the solid rock, the ore-bed is found. This is generally about 0·1–0·25 m. thick though occasionally it may reach as much as 1·00 m. At Banka and Billiton it usually contains 2–4 per cent of cassiterite. In the Malay Peninsula the deposits, when the overburden

is included, generally yield 0·1–0·15 per cent by weight of cassiterite. The principal minerals of this ore-bed are quartz, tourmaline, muscovite, hornblende, topaz, and sapphire; while, besides the tin ore, wolframite, scheelite, magnetite, and monazite often occur, and gold now and then. The material of the ore-bed is washed and concentrated in a primitive manner till a cassiterite concentrate with 68–73 per cent of metallic tin is obtained, this being often smelted on the spot.

These deposits of the Malay Peninsula were already known in ancient times, while in the Middle Ages they were worked to an extent sufficient to supply the large demand of China and India. Production in Banka began at the commencement of the eighteenth century, while in Billiton this was not the case till the early 'fifties of the nineteenth century. These two islands and the neighbouring small island of Singkep lie to the east of Sumatra, together with which they form part of the Dutch East Indies. The production of Banka has risen from 5000 tons annually during the years 1850–1880, to 10,000–12,000 tons per year latterly. From Billiton on the contrary the production, which from the 'seventies to the 'nineties was 4000–5000 tons per year, has fallen to 2000–2500 tons recently. The production of Singkep is small. In the Malay Peninsula, where mining in recent years has advanced so remarkably [1] and where railroads have been made to the most important occurrences, the deposits are distributed principally over the following federated States: Perak, Selangor, Negri Sembilan, Pahang, all of which with the exception of the last are on the west coast. The contributions of these different States are seen from the following table:

Malay States, Production of Tin in Pikuls [1]

	Perak.	Selangor.	Negri Sembilan.	Pahang.	Total.
1900	355,588	269,490	72,251	15,733	710,062
1901	385,065	302,598	75,241	22,339	785,243
1902	405,877	278,367	73,511	23,113	780,868
1903	436,242	292,664	85,465	25,275	839,646
1904	443,507	300,412	84,849	27,469	856,237
1905	446,781	289,867	85,133	34,879	856,660
1906	435,909	268,624	77,766	34,488	816,787
1907	431,386	273,900	75,155	33,195	813,636
1908	467,784	282,540	64,221	39,520	854,065

[1] Pikul = 60·5 kg.

From 1890 to 1905 altogether 11,374,841 pikuls or almost 700,000 tons of tin were obtained. In the latter year roughly one-half of the

[1] *Ante*, p. 424.

production from Perak was obtained from nine large mines of which six are entirely under European control. These and their outputs for 1905 are as follows :

	Pikuls:
Tronoh Mines	41,209
Kampar and Lahat	39,710
Tambun Mine, Ipoh	15,113
Gopeng	12,136
Duncan's Mine, Chanderiang . .	5,600
Bruseh	4,100
Foo Choo Choon's Mine . . .	40,000
Ny Boo Bee's Mine, Kamunting . .	13,178
Chang Ah Yong's Mine, Taiping . .	15,164
Total . .	186,210

Australia

In the different Australian States cassiterite deposits are well represented, this being particularly the case in Tasmania, New South Wales, and Queensland. In Victoria, Western Australia, and South Australia, tin mining, at least at times, is also undertaken. In New Zealand however cassiterite only occurs as a mineralogical curiosity.

The principal deposits are of the usual type, that of lodes either actually within or in the neighbourhood of granite, though exceptionally at Mount Bischoff the place of this rock is taken by quartz-porphyry. Near these primary deposits are others of detrital character, some of which are fluviatile, while others are eluvial. In Fig. 18 the relative disposition of the primary and secondary deposits to one another in one particular occurrence is illustrated. In relation to age it is probable that in some occurrences the gravel-deposits are Quaternary, while others, such as the deep-leads, are Tertiary, or more particularly Miocene.

Mount Bischoff in Tasmania

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The tin occurrence at Mount Bischoff, illustrated in Fig. 165, is economically the most important in Australasia. The steep conical hill of that name consists of early Palæozoic—probably Silurian—clay-slate and quartzite, with some sandstone and dolomite, these rocks being broken and traversed by a number of quartz-porphyry dykes which meet more or less radially to form the framework of the hill. Seventeen of such dykes are known. West of this hill and about 3·5 km. distant a granite mass comes to the

surface as part of a larger occurrence beneath. There can be no doubt that the quartz-porphyry dykes come from the same magma as this granite and that they therefore represent but another facies of that rock.

These same dykes since their intrusion have suffered an intense alteration within a circle of about 0·75 km. radius from the hill summit, beyond which, after gradual diminution of intensity from the centre, it is no longer observable. In this alteration all the original components with the exception of zircon have been destroyed, while topaz, tourmaline, secondary quartz, siderite, cassiterite, arsenopyrite, pyrite, pyrrhotite, fluorite, etc., have been formed. An analysis of the quartz-porphyry thus topazified gave roughly 35 per cent topaz and 65 per cent quartz, with no trace of felspar or mica. In this percentage of quartz a considerable portion is of secondary formation. The alteration appears to have proceeded in stages ; at first cassiterite and topaz were introduced, and then tourmaline, with which the siderite appears to be contemporaneous.

Pseudomorphs of the felspars are found consisting of a mixture of topaz, cassiterite, and other minerals. It is interesting to note that the quartz dihexahedra of the porphyry have likewise suffered an analogous pseudomorphism. The adjacent slates too are often tourmalinized, though on the other hand no formation of topaz has been observed in them. The major portion of the primary ore occurs in the altered quartz-porphyry dykes and only to a subordinate extent in the altered slates. There are however, in addition, true cavity-fillings in the immediate neighbourhood of the quartz-porphyry, some which are larger and many which are smaller. These carry cassiterite, wolframite, arsenopyrite, pyrite, quartz, topaz, fluorite, pyrophyllite, etc., while in addition the country-rock along their walls is distinguished by the amount of sericite it contains.

Mining however concerns itself but to a subordinate extent with the primary occurrences ; more important are the detrital or gravel-deposits which lie on the surface, and which, at all events in part, must be regarded as eluvial. The softer schistose material, surrendering more easily to the forces of disintegration and erosion than the more resistant porphyry, left the dykes of this material standing, till by reason of their inclination they broke and fell, exposing thereby their pieces to a more effective attack, which eventually left the cassiterite in relatively concentrated form. Fluviatile deposits also occur though such are of little importance.

Working in these detrital deposits are three opencuts, known respectively as White Face, Slaughter Yard Face, and Brown Face. The last-named occurs at the outcrop of a zone traversed by numerous cassiterite veins, forming an occurrence which may be regarded as intermediate between a gossan and an eluvial deposit. The sulphides here are decomposed to a depth of 90 m. or so, limonite thereby resulting.

Mining at Mount Bischoff began at the commencement of the 'seventies, soon after which, in consequence of the richness of the detrital deposits, the undertaking became a brilliant success. The principal company, the Mount Bischoff Tin Mining Company, in the 30 years between 1870 and 1900, distributed roughly £2,000,000 sterling in dividends. Up to the end of 1902 about 40,000 tons of tin had been produced. It is only recently, by reason of the exhaustion of the detrital deposits and because of the lower content of the primary deposit, that the production has receded.

The most successful tin field of Tasmania in recent years is that where, in a post-Silurian granite, the Blue-Tier mines occur. Some of the lodes there lie almost horizontal, showing thereby great resemblance to those of Zinnwald.[1]

The most important tin field of New South Wales lies in the Vegetable Creek district, near the Queensland border. In that field also, ore is only found in a contact-zone between granite and clay-slate, which zone according to Louis has a width of about 2·5 km. Roughly speaking one-third of the production so far from this colony has come from lodes, while the remainder has been derived from gravel-deposits.

The tin lodes of Queensland, both geologically and topographically, are a continuation of those in New South Wales just mentioned. Herberton district, which for many years past has yielded the largest portion of the total production, lies in a rocky granite country. The lodes carrying tin- and copper ores, together with wolframite, bismuth ores, etc., may best be compared with those of Cornwall.[2] Approximately two-thirds of the tin production of Queensland comes from lodes and one-third from gravel-deposits.

Tin mining in Victoria, Western Australia, and South Australia, is of less importance. At Greenbushes in Western Australia, as illustrated in Fig. 18, tin lodes, occurring in granite, are associated both with fluviatile and eluvial deposits. Tourmaline is strikingly abundant at this place, while the presence of niobium- and tantalum minerals renders the occurrence more than usually interesting.[3]

In Victoria and New South Wales tin was discovered in the year 1853. The cassiterite won was at first shipped; smelting in the country itself only began in 1867.

[1] Twelvetrees, 'Outlines of the Geology of Tasmania,' *Austr. Assoc. Ad. Sc.*, 1902; reviewed, *Zeit. f. prakt. Geol.*, 1902, pp. 273–278.

[2] W. Edlinger, 'Über die Zinnerzlagerstätten des Herberton-Distrikts,' *Zeit. f. prakt. Geol.*, 1908.

[3] Krusch, 'Zinnerzlagerstätten von Greenbushes,' *Zeit. f. prakt. Geol.*, 1903, p. 378.

United States of America

The occurrence of cassiterite has been established at many places in the United States, sometimes in primary deposits in close connection with granite, and sometimes in detrital deposits; but though mining has been attempted, it has never yet achieved any success, and to-day in this country, so rich in all other metals, no tin is produced.

The occurrence in the Black Hills of South Dakota have so far attracted the greatest attention. There within two small round granite masses a large number of coarse-grained pegmatite dykes or lodes occur which carry cassiterite, tantalite, a mineral thought to be columbite, arsenopyrite, auriferous chalcocite, quartz, orthoclase, albite, mica, spodumene, beryl, apatite, triphyline, etc. The crystals of spodumene are gigantic, sometimes reaching a length of 12 m. In general these lodes have a banded structure with mica on the walls.

As previously mentioned,[1] some authorities class these occurrences with the magmatic segregations. It is however rather a question of the introduction of certain ingredients, such as tin, tantalum, lithium, phosphoric acid, by pneumatolytic processes, such introduction having undoubtedly taken place during the magmatic period of the rock. The presence of greisen may also be observed.

Small amounts of cassiterite have also been won in Wyoming and in the Tewescal Mountains of South Carolina, in North Carolina, Maine, Hampshire, and in Alaska. Gravel-tin has been found in Montana and Idaho, and together with gold in California, Alaska,[2] and at other places.[3]

The tin occurrences in Mexico differ from the usual type in so far that they are not found in connection with granite but with rhyolite, the lava representative of the acid rocks. The mineral association is however the same as with normal granite. The deposits occur more particularly at Cacaria and Potrillas in Durango, and at Tescaltiche in Jalisco, but also at many other places, along joint-planes and fault-fissures in rhyolite and rhyolite tuff. They carry kaolin, quartz, chalcedony, opal, and felspar; together with specularite, fluorite, topaz, durangite, and more rarely wolframite and bismuth ore. Durangite is an arsenate of alumina and iron oxide, with sodium-lithium fluoride. It is worthy of remark that the tin won from these deposits contains a striking amount of antimony. Gravel-deposits have also been known in this country. Some tin was won as far

[1] *Ante*, p. 347.

[2] A. J. Collier, *U.S. Geol. Survey*, Bull. 259, 1905. A. Knopf, *ibid.*, Bull. 358, 1908.

[3] Cited in Kemp's *Ore Deposits*, *Mineral Resources of the United States*, and in *The Mineral Industry*; upon the Black Hills, especially W. P. Blake, *Amer. Journ. Sc.*, 1883, 1885; *Trans. Amer. Inst. Min. Eng.* XIII., 1885.

back as the time of the Aztecs, since when production has continued at different periods, though the amounts obtained however have only exceptionally been as much as 40 tons per year.[1]

In South Africa also cassiterite has been met in more than one place in granite or in the near neighbourhood of that rock; in the Transvaal for instance and in Swaziland. At the latter place the occurrence is in dykes of granite-pegmatite.[2]

The Wolfram Deposits

Wolframite, $(Fe, Mn)WO_4$, Hübnerite, $MnWO_4$, and Scheelite, $CaWO_4$, are found in most tin lodes, sometimes in such considerable amount that the wolfram ores are recovered as a valuable by-product with the cassiterite. Such is the case at Herberton in Queensland, in Cornwall, and at Zinnwald and Altenberg in the Erzgebirge. In addition, there are other lode-districts in connection with granite where wolframite is the principal ore and where cassiterite is subordinate, as for instance at Panasquiera in the Province of Beira Baixa, Portugal. Finally, there are other occurrences of wolframite where cassiterite is absent or practically so. All these lodes nevertheless must be classed with the cassiterite group.

As typically representative of those wolframite lodes which are without tin, the deposits described by Bodenbender as occurring at Sauce, Calumichita in the Sierra de Cordoba in the Argentine, may be mentioned.[3] There, at a height of some 1750 m. above the sea, sometimes in granite and sometimes in the surrounding crystalline schists, quartz lodes occur, containing wolframite, secondary scheelite, sulphide copper ores, molybdenite, sericite, quartz, apatite, fluorite, etc., but no cassiterite. The wolframite carries niobium. In the recent description of the wolfram-deposits in the Argentine by O. von Keyserling,[4] among other features attention was particularly called to the absence of cassiterite from these deposits. Tourmaline is found in quantity in some of the lodes, fluorite on the other hand seldom occurs, while topaz has only been established in one occurrence.

Beck[5] recently described wolframite-quartz lodes with tourmalinized country-rock in the outer contact-zones of a tourmaline-granite at Tirpersdorf near Oelsnitz in the Saxon Erzgebirge. In that district cassiterite

[1] W. R. Ingalls, 'The Tin-Deposits of Durango, Mexico,' *Trans. Amer. Inst. Min. Eng.* XXV., 1895, and XXVII., 1897; C. W. Kempton, *ibid.* XXV., 1895; Halse, *ibid.* XXIX., 1899; F. von Richthofen, *Zeit. d. D. Geol. Ges.*, 1869, p. 737; F. A. Genth, *Proc. Amer. Phil. Soc.* XXIV., 1887; J. L. Kleinschmidt, *Berg- u. Hüttenm. Ztg.*, 1883.

[2] L. de Launay, *Les Richesses minérales de l'Afrique*. Paris, 1903; H. Merensky, Papers, *Zeit. f. prakt. Geol.*, 1904, 1908; R. Beck and F. W. Voit, *ibid.*, 1906, 1908.

[3] *Zeit. f. prakt. Geol.*, 1894; *Bol. Acad. Nacional de Ciencias de Cordoba*, XVI., 1900.

[4] *Zeit. f. prakt. Geol.*, 1909.

[5] *Ibid.*, 1907.

is also absent as it is from some wolframite lodes occurring at Sadisdorf near Altenberg in the Erzgebirge, though the associated minerals, molybdenite, chalcopyrite, arsenopyrite, quartz, lithia-mica, fluorite, and apatite, are present.

According to *The Mining Industry*, XI., 1906, numerous quartz lodes with wolframite and scheelite occur in the Sorpresa mine, Las Caberas, Spain, along the contact between granite and Cambrian slate.

Some of the most productive wolfram mines in the United States at present are found in Boulder County, Colorado, where the ore occurs in close connection with some approximately parallel andesite dykes which traverse slate and granite. According to W. Lindgren however [1] these wolframite-quartz lodes may probably be connected with the granite. From this district about one-third of the world's production of wolfram is now derived. In Kern County, California, scheelite is exploited in lodes which at first were worked for silver and lead and which therefore in all probability do not belong to the tin-wolfram group. In Brazil near Encrucilhada, more particularly in the Progresso mine, wolfram lodes occur, which of late have been very productive. The ore there is accompanied by quartz.

The price of wolframite, in consequence of the increasing application of wolfram-steel, has latterly risen considerably. While in 1900 for ores with a minimum of 60 per cent WO_3 it was one shilling per kg. of WO_3, in 1906 it had risen to 3s. or 3s. 6d. per kg. Of late however it has fallen again.

The production of wolfram has latterly much increased and may be reckoned to be yearly some 3000–4000 tons of ore containing on an average 60 per cent of WO_3. The production for 1906, using in some districts the figures for 1905, was made up as follows: (1) from lodes of wolframite with little or no cassiterite: Boulder County, Colorado, about 750 tons; Beira Baixa, Portugal, 200–250 tons; Las Caberas, Spain, about 150 tons; the amount obtained from Tirpersdorf and Altenberg in Saxony is small; (2) from tin mines which recover wolframite as a by-product: Herberton district and other places in Queensland, 710 tons; New South Wales, 132 tons of wolframite and 138 tons of scheelite; Tasmania, 20 tons of wolframite; Cornwall, 250 tons; Zinnwald, some 50 tons; and the remaining occurrences decreasingly smaller amounts; (3) from the silver-lead-wolfram lodes of California, some 120 tons.

Molybdenite is not infrequently found in tin- and wolfram lodes, appearing especially to seek the company of wolframite. In addition, it occurs now and then with pyrite in separate quartz lodes in close connection with granite. Such an occurrence is found at the Knaben

[1] *Econ. Geol.*, 1907.

mine in Fjotland, southern Norway. Some molybdenum ore is regularly won in Norway, Australia, Canada, and other countries. Figures of price and production have already been given.[1]

Reference has already been made to the connection of the ores of uranium with wolfram deposits.[2]

The Cryolite Deposits of Ivigtut, Greenland

LITERATURE

F. Johnstrup. Discussion, Scandinavian Scientific Association, Stockholm, 1883.—F. Zirkel. Lehrbuch der Petrographie, III., 1894. p. 444.—O. B. Böggild. Mineralogia Groenlandica. Copenhagen, 1905.—N. V. Ussing. Geograf. Tiddsskrift, XIX. Copenhagen, 1907–1908. — C. F. Jarl. Celebration Publication. 'Fabrikken Öresund, 1859–1909,' the History and Development of the Cryolite Industry. Copenhagen, 1909.

The mineral cryolite, Na_3AlF_6 with 54·4 per cent of fluorine, forms at Ivigtut on the Arsut Fjord, along the south-west coast of Greenland, a well-known deposit 155 m. long and 30–55 m. wide, dimensions which are maintained in depth as far as mining operations have yet proceeded. The country-rock consists of gneiss, granite, and granite-porphyry.

In the central portion of the mass, cryolite, mixed with quartz, siderite, sphalerite, galena, chalcopyrite, and a little pyrite, predominates, the galena carrying about 0·7 per cent of silver. The pegmatitically-developed marginal portions, containing but little cryolite, consist of quartz and felspar together with the above-mentioned ores, and, in addition, wolframite, cassiterite, columbite, molybdenite, etc.; fluorite also is found though quite subordinately. As secondary minerals the following must be mentioned: tomsenolite, the hydrous Ca-Na-Al fluoride; pachnolite and gearsutite; ralstonite, the hydrous Na-Mg-Al fluoride; cryolitionite, the Na-Li-Al fluoride, etc. Besides the snow-white cryolite, grey or even almost black radioactive varieties sometimes occur.

Within the cryolite mass angular fragments of granite up to 3·5 m. in length occur, while the quartz-porphyry on the walls, for a foot or so, is altered to what may be termed a greisen. These phenomena, taken in conjunction with the presence of cassiterite, wolframite, and columbite, indicate that genetically this cryolite deposit must be regarded as a sort of facies of the tin group. This was indeed the view of Daubrée,[3] while later authorities, including Ussing so late as 1907–1908, have adopted the same view. It is worthy of remark that while in this deposit fluorine plays so important a part, minerals containing boron and phosphorus are absent. This is also the case with topaz.

This unique deposit was discovered at the end of the eighteenth century.

[1] *Ante*, pp. 207 and 208. [2] *Ante*, p. 423.

[3] *Géol. expérim.*, 1879, p. 31.

In 1854 mining by opencut was begun, which opencut to-day has reached a depth of about 45 m. Altogether some 350,000 tons of cryolite have been exported, of which amount 307,731 tons had been obtained up to the year 1901. The roughly sorted ore, consisting of about 90 per cent of cryolite, 5 per cent siderite, 3–4 per cent quartz, and 1 per cent of galena, sphalerite, chalcopyrite, and pyrite together, is sent to Copenhagen to be there more carefully concentrated. Cryolite with about 2 per cent of silica is used in the manufacture of opalescent glass, and of enamel for iron-ware ; while a considerable amount, not containing more than 0·2 per cent of silica, is used in the production of aluminium. Formerly also, the raw material was particularly used in the production of soda.

In addition to the occurrence just described, cryolite has also been shown to occur in a topaz mine in the Ilmenite Range of the Ural Mountains. It has further been found at Pike's Peak, Colorado, with microcline, astrophyllite, columbite, etc. ; [1] and also in the Yellowstone Park.

The interesting occurrence of smaragdite at Minne, in Eidsvold, Norway, where the presence of topaz has also been established, belongs genetically to the tin group in the wider sense of the term. Though the same may also be said of some other smaragdite occurrences, it is nevertheless the case that the most important deposits of this mineral occur in contact-metamorphic mica-schists, such deposits having no connection whatever with the tin group.

Apatite Lodes within or in the Neighbourhood of Granite

The phosphates so characteristic of the tin lodes, and especially apatite, amblygonite, triphyline, etc., occasionally occur in those lodes in considerable amount. Apatite for example occurs plentifully in the tin lodes of the Black Hills, Dakota.[2] In some of the granite-pegmatite dykes of southern Norway, apatite as a by-product has also been recovered with microcline. About the year 1900 some tin mines in Montebras, France, were worked chiefly for amblygonite, this mineral being employed in the production of lithia preparations.

In the province of Estremadura in south-west Spain, and in the adjacent province of Alemtejo in Portugal, apatite-bearing quartz lodes are known, such as probably are genetically connected with granite. Some at Marvão, Portalegre, Zarza, Ceclavin, and Zarzala Major, occur actually in granite, while others, as at Logrosan, occur in slate, though in the neighbourhood of granite. Mining operations upon these occur-

[1] Whitmann Cross and Hillebrand, *Amer Jour. Sc.* XXVII.
[2] *Ante*, p. 447.

rences formerly produced as much as 20,000 tons of apatite per year.[1] Latterly however the production from Spain has greatly diminished, while that from Portugal has entirely ceased.

Of quite another geological position is the occurrence at Jumilla in Murcia, Spain, recently described by A. Osann.[2] There, in a basic eruptive rock rich in sanidine and leucite, which rock Osann termed 'jumillite,' a network of veins occurs, which veins are particularly rich in apatite and calcite. Along these the jumillite is altered. This occurrence some decades ago was worked down to a depth of some 50 m., for apatite.

Apatite Lodes within or in the Neighbourhood of Gabbro

LITERATURE

Norway: W. C. Brögger and H. Reusch. Zeit. d. D. Geol. Ges., 1875; and Nyt. Mag. f. Naturv. XXV., 1880.—H. Sjögren. Geol. Fören. Förh. VI., 1883; VII., 1884.—J. H. L. Vogt. Ibid., VI., 1883; XIV., 1892; and particularly Zeit. f. prakt. Geol., 1895, pp. 367-370, 444-459, 465-740.—A. Lacroix. Bull. de la Soc. fran. de min. XII., 1889.

Gellivara-Dundret: Swedish Commission's Report, 1890, 1892 (cit. ante).—W. C. Brögger, G. Löfstrand, Hj. Lundbohm, H. von Post, F. V. Svenonius, etc. Geol. Fören. Förh., 1889–1892.

Canada: F. D. Adams and A. C. Lawson. 'On some Canadian Rocks containing Scapolite, with a few notes on some Rocks associated with the Apatite Deposits,' Can. Rec. of Sc., 1888.—Sterry Hunt. Reports to Geol. Survey, Canada, 1863–1866.—B. J. Harrington, G. C. Hofmann, E. Coste, Director Selwyn, R. W. Ells, E. D. Ingall. Reports, Geol. Survey, Canada.—J. W. Dawson. Quart. Jour. Geol. XXXII., 1876.—R. A. F. Penrose. U.S. Geol. Survey, Bull. 46, 1888.—R. W. Ells and J. Burley Smith. Min. Assoc. Province Quebec, 1891, 1892, 1893.—Ells. Can. Rec. of Sc., 1895.—A. Osann. Geol. Survey, Canada, 1902.

In the fundamental rocks of south-east Norway, within the coastal district about 110 km. long and 25 km. wide which stretches between Lillesand and Langesund, a large number of apatite lodes are found of which however but few reach any great size. Smaller lodes are also known at Nissedal and Snarum farther to the north in Norway, and around Dundret near Gellivara in northern Sweden.

It is characteristic of all these lodes that they occur either within or in the closest proximity to a gabbro rock, generally an olivine-hyperite, that is olivine-gabbro with ophitic structure. Less frequently they are found in gabbro or olivine-gabbro of normal texture, but never in norite.

The lode material, mineralogically, is distinguished by the occurrence of chlor-apatite, rutile, ilmenite, pyrrhotite, enstatite, hornblende, biotite, scapolite, and more seldom of wagnerite Mg_2FPO_4, felspar, quartz, augite, pyrite, chalcopyrite, specularite, magnetite, titanite, yttrotitanite, pseudo-

[1] Fuchs and de Launay, Vol. I., p. 348; Hernandez Pacheco, 'Los filones estanniferos de la provincia de Caceres,' *Bol. Soc. Esp. de Hist. Nat.* II., 1902; *Zeit. f. prakt. Geol.*, 1907, p. 209.

[2] Pamphlet issued at the Rosenbusch celebrations, 1906.

brookite, prehnite, calcite, tourmaline, etc. Of interest also is the fact that in some of the lodes at Oedegaarden, thorite has been demonstrated to occur. These many minerals often occur in very large individual crystals, those of enstatite for instance being sometimes as much as 0·4 m. long. Their arrangement also is often in such bands or crusts as were remarked with the tin lodes, having in this case however, as illustrated in Fig. 276, mica and hornblende towards the walls and apatite in the centre. The lodes actually within the gabbro, as illustrated in Fig. 277, follow in general the ordinary joints and contraction-planes of the rock, in which again they behave similarly to the tin lodes. Those occurring in the surrounding gneiss on the other hand generally maintain a direction more or less parallel to the schistosity, though frequent exceptions to this rule are observable. Where the walls are of gabbro it is usual to find this rock altered to a scapolite-hornblende rock, or to one containing scapolite, enstatite, etc. Cases of this are illustrated in Figs. 276, 277, and 278. Where the lodes are numerous and close together, as at Oedegaarden in Bamle, the olivine-hyperite which envelops them is, as illustrated in Fig. 279, almost entirely altered. In the process of this metamorphism the diallage, and perhaps also the olivine,

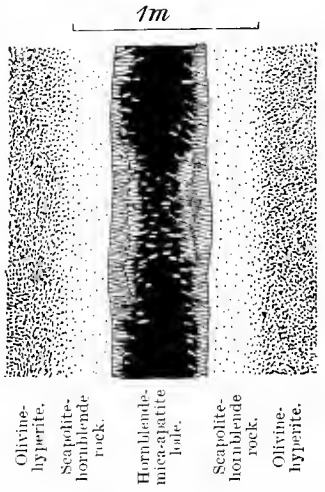

FIG. 276.—Apatite lode at Regaardshei showing hornblende and mica on the walls, and apatite in the centre. Vogt, *Zeit. f. prakt. Geol.*, 1905.

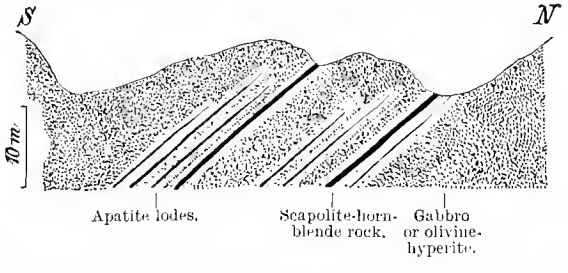

FIG. 277.—Section at Husaas in the neighbourhood of Risör. Vogt.

is altered, chiefly to hornblende, and the plagioclase, by the addition of some 4–5 per cent of NaCl, to scapolite, while the iron minerals of the primary rock are in greater part leached. This alteration is also often rendered the more complete by the introduction of secondarily formed rutile.

The lodes again exhibit quite a number of different facies. The most widely distributed are the apatite lodes proper, containing that mineral together with some hornblende, enstatite, and mica. With a few, wagnerite predominates. Others contain apatite with much rutile, much pyrrhotite, or much specularite. In addition there are lodes which consist almost exclusively of rutile, or pyrrhotite and rutile, or specularite alone. In this connection the rock krageröite, described by Brögger as consisting of rutile with a moderately acid plagioclase,[1] deserves mention.[2]

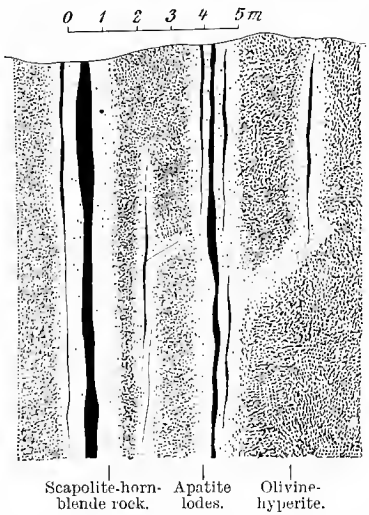

FIG. 278.—Apatite lodes in olivine-hyperite at Regaardshei; compare Fig. 276. Vogt.

Without doubt the most important apatite field in Norway is that of Oedegaarden in Bamle, from which since 1872 about 140,000 tons of apatite, pure to the extent of about 97 per cent, have been produced. In some years the output reached as much as 10,000–15,000 tons, while in other years it has been as low as 2500 tons. The mines are now approximately 150 m. deep. The rutile occurrences produced about 100 tons annually.

From the invariable association of the apatite lodes with gabbro at

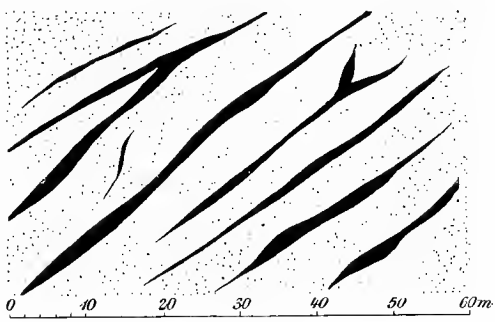

FIG. 279.—Apatite lodes in scapolite-hornblende rock at Oedegaarden. Vogt.

so many different places, it follows that they are genetically connected with that rock, as the tin lodes are with granite.[3]

The Canadian apatite lodes in the fundamental rocks between Kingston

[1] *Ges. d. Wiss.*, Christiania, Dec. 1903.

[2] *Ante*, p. 278.

[3] *Ante*, pp. 420, 421.

and Ottawa resemble the Norwegian occurrences in their principal features, though at the same time they present a number of divergent properties. They are found in close association with so-called pyroxenite, a sort of gabbro rock. The apatite is fluor-apatite with a small chlorine content; augite occurs, but no enstatite; then occur biotite, scapolite, felspar, quartz, calcite, titanite, ilmenite, different sulphides, or altogether a mineral-family identical, in general at all events, with the occurrences in Norway. In Canada also a secondary formation of scapolite in the country-rock has been observed, though one by far not so characteristic as that with the Norwegian occurrences. In view of these facts the present Canadian investigators, and with them Osann, have applied the theory of genesis evolved for the Norwegian occurrences, to those of Canada.

The Canadian production from 1860 to 1890 varied between 20,000 and 30,000 tons per year, since when however, in consequence of the drop in the price of phosphates, it has fallen to a very low figure.

ANNEX

The following table of those minerals of the augite-syenite and nepheline-syenite pegmatite dykes, as are distinguished particularly by containing ZrO_2, B_2O_3, and F, taken from Brögger's work in 1890,[1] is inserted here as being pertinent to the discussion of the formation of minerals by pneumatolytic addition, during the consolidation of a magma. Almost the same mineral-family is found in the petrographically corresponding district of Kangardluarsuak in Greenland. As is seen, many of the pneumatolytic minerals of the augite- and nepheline-syenites are characterized by halogen elements, a fact which constitutes a further analogy between the genetically corresponding minerals of granite on the one side and those of gabbro on the other. In addition, boric acid often appears, and in one case much stannic oxide. There is however this essential difference, that the tin, wolfram, etc., of the pneumatolytic deposits associated with granite, and the titanium, phosphorus, etc., of those with gabbro, are in the case of the augite- and nepheline-syenite dykes replaced more particularly by zirconium and thorium. This is a phenomenon which probably is referable to the composition of the parent magma of the rock concerned.

[1] *Zeit. f. Krist. u. Min.* Vol. XVI.

[TABLE.

	Per cent F.	Per cent Cl.	Per cent B_2O_3.	Per cent As.	Per cent S.	Per cent ZrO_2.	Per cent SnO_2.
Rosenbuschite	5·83	...	...	...	...	20·10	...
Låvenite	3·82	...	...	...	...	30·00	...
Wöhlerite	2·98	...	...	...	...	16·10	...
Hiortdahlite	5·83	...	...	...	...	21·50	...
Mosandrite	2·60	...	...	...	...	2·80	...
Johnstrupite	5·98	...	...	...	...	...	...
Pyrochlore	about 4·00	...	...	...	...	...	...
Melinophane	5·43	...	...	...	...	...	...
Leucophane	5·94	...	...	...	...	...	...
Astrophyllite	0·97	...	...	...	...	...	...
Fluorite	48·72	...	...	...	...	...	...
Melanocerite	5·78	...	3·19	...	...	0·50	...
Karyocerite	5·63	...	4·70	...	...	0·50	...
Tritomite	3–4	...	7–8	...	...	1·10	...
Tourmaline	about 0·75	...	about 9·00	...	...	...	...
Erdmannite (so called)	...	...	about 8·00	...	...	...	...
Homilite	...	...	16·51	...	...	...	...
Cappelinite	...	...	17·13	...	...	...	...
Datolite	...	...	21·88	...	...	...	...
Nordenskiöldine	...	...	25·33	...	...	0·90	53·70
Hambergite	...	...	37·16	...	...	...	...
Eukolite	...	1–2	...	...	...	15·30	...
Sodalite	...	7·31	...	...	...	...	...
Helvite	...	...	...	...	5·71	...	...
Löllingite	...	...	...	72·17	0·37	...	...
Molybdenite	...	...	...	...	41·03	...	...
Sphalerite	...	...	...	...	33·00	...	...
Iron-pyrite	...	...	...	...	53·33	...	...
Galena	...	...	...	...	13·40	...	...
Chalcopyrite	...	...	...	...	34·89	...	...
Polymignite	...	...	...	...	...	29·70	...
Katapleite	...	...	...	...	...	29–40	...
Zircon	...	...	...	...	...	67·00	...

THE QUICKSILVER GROUP

LITERATURE

G. F. Becker. 'Quicksilver Deposits of the Pacific Slope,' U.S. Geol. Survey, Mon., XIII., 1888; Supplemented, Mineral Resources of United States, 1892.—A. Schrauf. 'Aphorismen über Zinnober,' Zeit. f. prakt. Geol., 1894, p. 10.—P. Krusch. 'Vorkommen und Entstehung der Quicksilbererze,' Prometheus, 1896, pp. 437, 458.

Generally speaking, two kinds of quicksilver deposits may be differentiated, firstly that in which the metal occurs in the form of cinnabar, and to this kind by far the greater number and the most important occurrences belong; and secondly that where quicksilver is an essential constituent of tetrahedrite, as for instance at Schwaz in the Tyrol, in the Zips mountains of northern Hungary, and in Bosnia, etc.

As already stated in the section upon ores,[1] cinnabar is also formed in the oxidation zone from the decomposition of tetrahedrite. Though therefore a deposit which contains cinnabar near the surface may also carry that mineral in depth, there is the possibility that tetrahedrite may there be found to occur. When developing such outcrop occurrences therefore, it is necessary to determine whether or not other heavy-metal compounds are present. While the primary cinnabar occurrences are poor in all such heavy metals, in the case of tetrahedrite on the other hand, copper plays an important part.

Besides cinnabar other combinations of quicksilver are found in small amounts in the deposits of that mineral; native quicksilver for instance, which is generally secondary and the result of tectonic or chemical-geological processes upon the primary ore; silver-amalgam, as at Moschellandsberg near Rheinpfalz, and at Idria, etc.; and some very infrequently occurring selenium- and tellurium ores. Metacinnabarite, occurring in some mines in California, at Huitzuco in Mexico, at Moschellandsberg in Italy, and in New Zealand, is, according to Schrauf, the relatively light cubically crystalline modification of mercuric sulphide such as is formed for instance by the action of sulphuretted hydrogen upon the metal.

[1] *Ante*, p. 84.

As seen from the table on the opposite page, compiled by Becker in 1892 and supplemented by Schrauf in 1894, of all the heavy-metal sulphides, pyrite, occasionally with marcasite, is the most frequent associate of cinnabar; in comparison with it, galena, sphalerite, and chalcopyrite fall far behind. On the other hand stibnite, and now and then other antimony ores, and such arsenic ores as realgar, orpiment, and arsenopyrite, are well represented. In some of the younger quicksilver deposits gold and silver also are found, though in most cases they are absent.

By far the most frequent gangue mineral is quartz, which is accompanied by chalcedony and opal. After quartz come calcite and dolomite, then barite and selenite, while fluorite is exceptional. Most singular and important is the frequent occurrence of bitumen in the form of different hydro-carbons. This association, in conjunction with the fact that bitumen precipitates cinnabar from solfataras, makes it likely that this material plays genetically a very important part.

Becker rightly called particular attention to the fact that most quicksilver deposits occur along pronounced tectonic lines. This is especially plainly to be seen from the disposition of the North American occurrences, which lie on the west slope of that continent, that is along a mountain chain which has been subject to intense geological disturbance.

Most occurrences again are associated with young eruptive rocks: those of California with basalt, andesite, and in one case with rhyolite; those of Mexico, it is stated, with pitchstone-porphyry. In Texas they are found in the neighbourhood of andesite and trachyte; in Peru, of trachyte; and in the Monte Amiata district, Tuscany, of young eruptive rocks and their tuffs. At Vallalta in northern Italy, quartz-porphyry occurs; near Almaden, diabase; while on the Avala hill near Belgrade the ore is closely connected with serpentine.

As with the gold- and silver-deposits, there is likewise some justification for dividing the quicksilver-deposits into a younger and an older group. The first, extending from and including the Tertiary, is represented particularly in California, Texas, Mexico, Peru, Italy, Persia, Japan, New Zealand, etc., while in Idria the deposit also appears to be fairly young. To the older group belong the deposits at Almaden in Spain, Moschellandsberg in the Rheinpfalz, and Nikitovka in southern Russia. Mineralogically and genetically however no differences exist between the two groups, which consequently may not be considered apart.

In relation to the manner of their occurrence, the deposits of cinnabar may be differentiated from those of quicksilver-bearing tetrahedrite. These latter at all points resemble the sulphide lead, silver, zinc, or copper lodes, and accordingly appear as simple or composite lodes of varying thickness. With the cinnabar deposits on the other hand the filling of the fissures up

QUICKSILVER OCCURRENCES COMPILED BY BECKER

Place.	Geological Formation.	Antimony Ore.	Barite.	Galena and Sphalerite.	Calcite.	Iron Oxide.	Carbon Bitumen, etc.	Pyrite.	Quartz.	Sulphur
Bohemia (Hořowitz) .	Silurian	...	...	...	...	Dominating	...	Seldom	...	...
Borneo . .	Palæozoic	Dominating	Frequent	...	Dominating	...	...	Frequent	...	...
Bosnia . . .	Triassic	Dominating	...	Frequent	Dominating	...	...	...	Dominating	...
California . .	Cretaceous and Tertiary	Seldom	Seldom	...	Frequent	...	Frequent	Dominating	Dominating	Seldom
Germany (Rheinpfalz) .	Carboniferous	Seldom	Frequent	Seldom	Frequent	...	...	Dominating	Dominating	Seldom
Idria . . .	Triassic	...	Seldom	...	Dominating	...	Frequent	Frequent	Frequent	...
Italy . . .	Eocene	...	...	...	Dominating	...	Seldom	Frequent	Seldom	Seldom
Peru (Huancavelica)	Jurassic	...	Frequent	...	...	...	...	Frequent	Dominating	...
Russia (Nikitovka) .	Carboniferous	Dominating	...	...	...	...	Frequent	...	...	...
Servia (Avala) .	Serpentine	Frequent	Seldom	Seldom	Frequent	...	...	Frequent	Dominating	...
Spain (Almaden)	Silurian	...	Seldom	...	...	...	Seldom	Frequent	Dominating	...
Kärnten - Steiermark .	Triassic	...	...	...	Dominating	Dominating	...	...	...	...

which the quicksilver solutions ascended, usually plays but a small part, impregnation of the country-rock being the principal form of the occurrence. Of such impregnation there are, according to the nature of the country-rock, two types: the quicksilver either fills the pores of porous rocks such as sandstone, quartzite, or conglomerate; or it occurs in shattered limestone filling the crevices so completely that the rock throughout is veined with ore.

To the first type belong: Almaden, the most important occurrence in the world; Nikitovka; Huancavelica; the Pfalz deposits, etc. Such ores are also known to occur in California, Italy, and the Asturias. With these deposits the displacement of the siliceous constituents of sandstone and quartzite by the ore is such, that large, entirely metasomatic bodies of pure or almost pure cinnabar may take the place of sandstone, a rock which chemically and geologically is usually so resistant. The rich ore-bodies of Almaden for example are thus to be explained. Mechanically and chemically the deposits of this type provide the cleaner ore.

The impregnations in limestone show no such striking metasomatis, and with them, therefore, large pure masses of ore are rare. Equally so are wide fissure-fillings. Where these latter do occur, as for instance in the south-east mine at Idria and in California, the ore itself occupies but a fraction of the filling, which filling consists chiefly of breccia.

A differentiation of cinnabar ores may also be based on their different colour. On account of their close connection with bitumen on the one side and with limestone on the other, two classes may be discriminated; the one more or less dark, because of the large amount of bitumen contained; and the other more or less scarlet according as cinnabar or limestone predominates. To the first class belong quicksilver lebererz and the almost black korallenerz.

Concerning the origin of quicksilver deposits, an important factor is the relation of these to large tectonic disturbances and to places of great volcanic activity. In addition, the frequent association with sulphides, and very exceptionally also with selenides and tellurides, is significant. It is also important in this connection that, apart from chlorine and fluorine combinations quite small in amount, all those minerals characteristic of the tin lodes are absent. Fluorite for instance is extremely seldom met, while such chlorine compounds as calomel and the complex compounds of mercury occur as the greatest rarities, when, even then, they may be secondary.

From the frequent occurrence of cinnabar in porous and shattered rocks the conclusion may unhesitatingly be drawn that these rocks were saturated with solutions carrying quicksilver.

Naturally with many deposits of the older group it is in many cases no

longer possible to come to any conclusion regarding the extent to which volcanic and thermal phenomena participated in their formation. With the younger group on the other hand there are a number of localities where the intimate association with young volcanic rocks and thermal deposits is actually observable. To these latter belong the Californian deposits, Sulphur Bank, Moncanita, Redington Valley; those at Steamboat Springs in Nevada; several in Mexico; Huancavelica in Peru; others in New Zealand, at Monte Amiata, and in Persia. Of special importance genetically are the occurrences at Sulphur Bank and Steamboat Springs, where hot springs still continue to deposit quicksilver.[1] In New Zealand also two warm sulphur springs are known in process of impregnating sandstone with cinnabar and of coating the sides of a fissure with metacinnabarite and native quicksilver. Conformable to this observed association with eruptive rocks, springs and spring deposits containing quicksilver compounds are found at other places. Such for instance is the case with the fumaroles of Puzzuoli near Naples, and the thermal springs of St. Nectaire, Puy de Dôme, France.

The hot springs at Sulphur Bank and Steamboat Springs contain sodium chloride plentifully, together with some carbonate and sulphate, and in addition so much boric acid that borax becomes precipitated. They further contain sodium sulphide and various sulpho-salts of arsenic and antimony. Traces of quicksilver may also at times be detected analytically in hot springs from which carbonic acid, sulphuretted hydrogen, sulphur dioxide, and other gases are escaping. As with all such solfataras, on account of insufficient oxidation and the consequent interaction between H_2S and SO_2, native sulphur becomes precipitated where they emerge. Cinnabar on the other hand is deposited before the surface is reached.

Becker is of the opinion that in these recent hot springs cinnabar is not present as a mechanically involved sulphide nor as a dissolved chloride, but rather as a soluble double-sulphide of the formula $HgS \cdot nNa_2S$. He and Melville have demonstrated experimentally that HgS is somewhat soluble in a hot solution of $Na_2S + H_2S$, though not in cold NaHS.

Precipitation of the cinnabar takes place either by evaporation of the solution; by oxidation; by escape of the sulphuretted hydrogen consequent upon the decomposition of Na_2S; or finally, by the reducing action of hydrocarbons.[2] Simultaneously with the cinnabar, other sulphides such as Sb_2S_3, resulting from the decomposition of the sulpho-salts, would be precipitated, together with silica and calcium carbonate. For the further understanding of the conditions obtaining at the formation of cinnabar it must be pointed out that L. de Koninck [3] by slow oxidation,

[1] *Ante*, p. 182. [2] *Ante*, p. 458.

[3] *Zeit. f. angew. Chem.*, 91.

namely by placing HgS in the open with Na_2S, obtained crystals of cinnabar 1 mm. in size. Weinschenk also,[1] by the action of sulphuretted hydrogen at a temperature of 230°–250° C. and under high pressure, produced good cinnabar crystals from a quicksilver solution.

The theory promulgated by Becker in regard to the Californian, Mexican, and Peruvian occurrences, may also be taken to hold good for the majority of the older deposits. The question of the genesis of quicksilver ores in general is thus more firmly grasped than is the case with the majority of the other lode-like deposits. Though, however, this may be so, nevertheless, the actual source of the quicksilver and the chemical processes which led to its extraction remain unknown. With regard to the Californian occurrences, Becker in advancing the suggestion that the heated waters derived their quicksilver from granite situated below, ventured an hypothesis which from the nature of the case could but lack secure foundation. The pronounced connection of these deposits, monotonous in character and widely distributed as they are, with eruptive rocks, and their occurrence along tectonic lines, make it probable that the source of the quicksilver is everywhere deep-seated and the same, and that the extraction of the metal took place directly out of the magma of the eruptive rocks concerned.

The quicksilver deposits are in greater part of young formation and have arisen comparatively speaking near the surface. Such circumstances of formation postulate a fairly sharp line between them and the deposits of other ores, though at Steamboat Springs, at the Comstock Lode,[2] and at several places in Mexico, Peru, and the Carpathians, young quicksilver occurrences are found together with young silver-gold lodes. Even in these cases however it must not be overlooked that the ores carried in the two classes of deposit are quite different. Silver-gold ores occur extremely seldom in quicksilver deposits, while quicksilver usually is entirely wanting in the young as well as in the old silver-gold lodes. Tetrahedrite however which may contain material quantities of both silver and quicksilver, may, when it is present, perhaps be regarded as a transition ore. It must also be remarked in this connection that the native silver of Kongsberg in Norway often contains quicksilver, and that in the metasomatic silver-lead deposits at Sala in Sweden, silver-amalgam, native quicksilver, and in some places cinnabar especially, occur, though only in very small amount.[3]

In relation to the quicksilver content, Almaden with an average of 8 per cent is unique; all other deposits contain considerably less. At New Almaden in California, the content is 2 per cent; at Idria, about 1 per cent; at Nikitovka, 0·75 per cent; and at Vallalta in Lombardy,

[1] *Zeit. f. Krist. Min.* XVII., 1890
[2] *Postea*, p. 467.
[3] Hj Sjögren, *Geol. Fören. Förh* XXII., 1900.

about 0·50 per cent of the material hoisted. With some deposits, particularly Almaden and Idria, the percentage of quicksilver has increased in depth, while with others, such as those at Moschellandsberg and some in Asia Minor, the deposit in greater depth has become unpayable. The statistics given previously on pp. 202, 203, and 207, 208, are completed below by figures taken from Becker, B. Neumann,[1] and from the yearly statistics of the *Metallgesellschaft* and the *Metallurgische Gesellschaft*, Frankfort.

World's Production of Quicksilver

In Metric Tons

	1800.	1850.	1870.	1890.	1900.	1905.
Almaden	844	about 880	1345	1813	1095	834
Idria	402	142	370	542	510	570
Hungary	...	42	26	8	32	
Italy	...	...	47	449	260	352
Russia	...	...	...	292	304	318
California	...	964 (for 1851)	1044	795	910	1043
Texas	...	...	...	...	70	
Mexico	...	...	...	61	124	190
Peru	a little	...	...	...	...	...
Total tons	about 1300	about 2000	2800	3950	3300	3300

The total outputs of the most important mines are as follows:

	Tons.
Almaden, 1564–1907	169,000
Idria, 1525–1908	72,000
California, 1850–1908	73,000
Huancavelica, 1571–1825	52,000

Quicksilver is sold by the flask,[2] the content of which varies somewhat in different countries. In Spain it contains 34·5 kg.; in California, Russia, and Italy, 34·7 kg.; and in Mexico, 34·05 kg. The average price per kg. in Europe has been as follows:[3]

	s.	d.	
1816–1835	3	6	per kg.
1836–1852	7	0	,,
1853–1870	4	1	,,
1871–1875	8	0	,,
1876–1900	4	0	,,
1901–1908	4	3	,,

[1] *Die Metalle*, 1904.

[2] *Ante*, p. 208, and *postea*, p. 468.

[3] *Ante*, p. 208, and *postea*, p. 468.

The Quicksilver Deposits of California; including Steamboat Springs

LITERATURE

G. F. Becker. 'Quicksilver Deposits of the Pacific Slope,' U.S. Geol. Survey, Mon., XIII., 1888; 'Quicksilver Ore Deposits, Mineral Resources of the United States,' 1892, p. 139.—P. Krusch. 'Vorkommen und Entstehung der Quicksilbererze,' Prometheus, 1896, pp. 437, 458.—W. Forstner. 'The Quicksilver Deposits of California,' Eng. and Min. Jour., 1904, p. 385.

These deposits occur along the Californian sea-board where the country in general consists of strongly metamorphosed Neocomian sandstone and slate. Of the eruptive rocks present, the granite, which apparently underlies the whole district, shows itself, both in the Coast Ranges and at Steamboat Springs, to be quite coarse-grained. Other pre-Tertiary eruptive rocks are, porphyry in the Coast Ranges and diabase at Steamboat Springs, while young lavas are represented in both places by andesite, basalt, and rhyolite.

According to Becker, the alteration of the strata, which in their original condition yield specimens of the fossil genus *Aucella*, took place towards the end of the Neocomian period when the folding began which continued till the middle of the Cretaceous. Later, in Tertiary times, the whole district was once again visited by far-reaching tectonic movements. Of the different rocks mentioned, the sandstone, which fully participated in all the alteration occasioned by these disturbances, is the most important carrier of the cinnabar.

The disposition of the deposits is as follows: to the north, at Clear Lake, Sulphur Bank, the Knoxville district, Great Western, and Great Eastern; farther to the south, at New Almaden and New Idria; and finally, farther to the east, at Steamboat Springs, all these places being indicated on the map which constitutes Fig. 280.

In connection with the young eruptive rocks, hot springs in great number break forth, which in themselves, and in the sometimes beautifully coloured sinter which they deposit, impart a unique character to the landscape.

The neighbourhood of Clear Lake is characterized by lava flows, volcanic peaks, deposits of borax, and thermal springs. The sediments belong to the Neocomian, to the Upper Cretaceous represented here by the Chico Series, and to the Eocene represented by the Tejon. The borax deposits and the hot springs, as well as the deposits of cinnabar and native sulphur, are connected with basalt eruptions. At Sulphur Bank, quite close, there is also a similar basalt occurrence accompanied by hot solfataras. A little to the south-east, at Knoxville, the deeper portions of the much metamorphosed Neocomian sandstone carry cinnabar. The upper layers

of this sandstone and the lower portion of the weathered basalt lying upon it are impregnated with a mixture of cinnabar and sulphur, while the uppermost portion of the basalt carries sulphur only, which, even to-day, as the result of the oxidation of sulphuretted hydrogen, continues to separate. In addition to cinnabar the ore consists of pyrite and marcasite, with quartz, chalcedony, and calcite, as gangue.

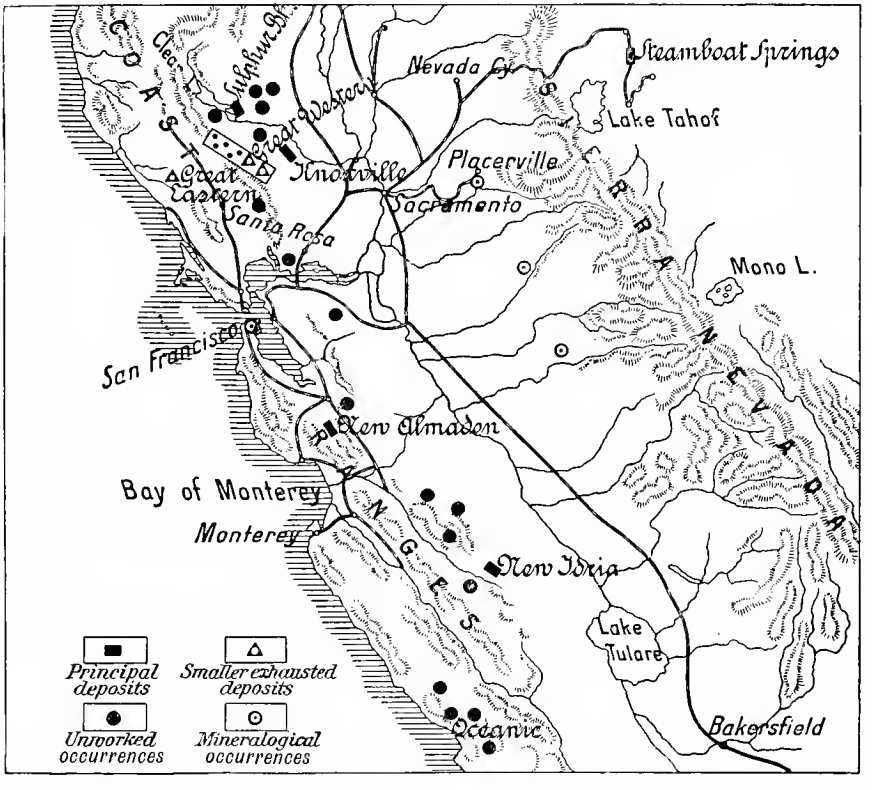

FIG. 280.—General map of the quicksilver deposits of California. Becker.

At the Redington mine two fissures with cinnabar filling, form the essential part of the occurrence. At one place there, solfatara gases still escape, while borax-springs are common. It is interesting to note that the California mine in the same district formerly produced much metacinnabarite. At Oat Hill there are several mines. The sediments at that place belong to the serpentinized Knoxville sandstone of the Neocomian formation; they have been broken by andesites and basalts. At Lidell hot springs are still active. The principal mine works a deposit occurring in

sandstone, which lies almost horizontal and is traversed by veins dipping less than 45°. From these veins the ore extends into the rock, principally

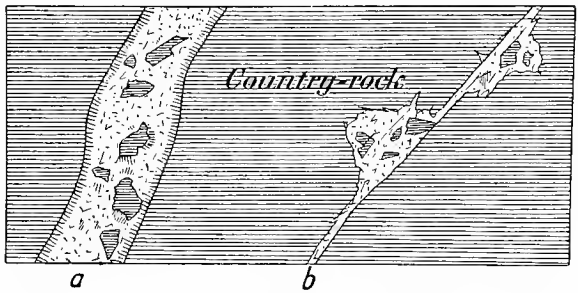

FIG. 281.—Form of the quicksilver lodes in California. Becker.

a, Normal lode; *b*, chamber lode.

along the bedding-planes. The Great Western and Great Eastern mines carry cinnabar both in the serpentinized sandstone and in that which is unaltered. The ore in the latter mine has been followed to a depth of 450 feet.

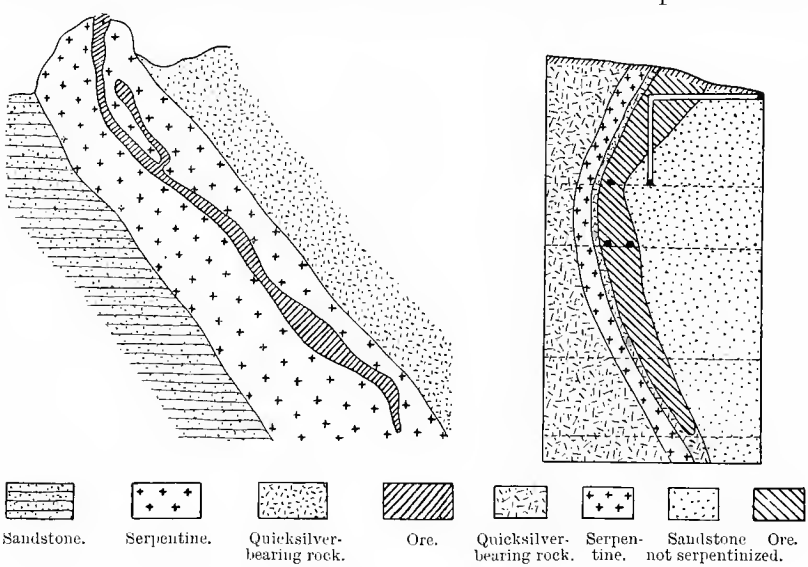

FIG. 282.—Sections of the Great Eastern mine, California. Becker.

Farther to the south comes the New Almaden district, the richest in California. Here, lying upon metamorphosed rocks of the Lower Cretaceous formation, much-folded Miocene sandstone is found intruded by a rhyolite which is stated to be the only occurrence of this rock in all

California. In that sandstone numerous veins forming a complex system carry cinnabar, pyrite, marcasite, quartz, and calcite, with which minerals at the same time a large width of the fractured country-rock has become impregnated. The New Almaden mine, which in 1885 was already 650 m. deep, produced during the period 1850–1897 some 34,000 tons.[1]

The New Idria district is centred around one of the highest points of the Coast Ranges, at the southern end of the Diablo Mountains. The upper portion of the hill consists of metamorphosed Knoxville sandstone belonging as stated before to the Neocomian, while on the north-eastern flank the Chico Series of the Upper Cretaceous and the Tejon of the Eocene are found.

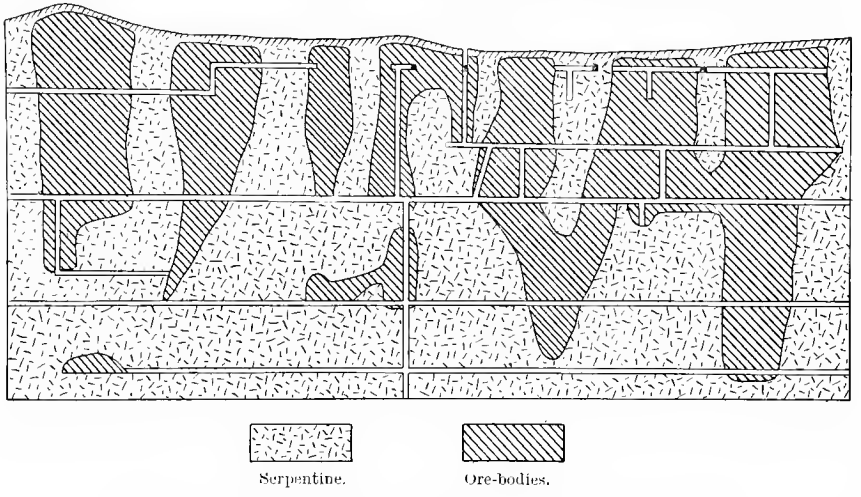

FIG. 283.—Section of the Great Western mine in California. Becker.

The ore occurs in veins or vein-networks and in impregnation zones, within the Neocomian. In this occurrence bitumen in addition to quartz plays an essential part. About 16 km. away cold sulphur-springs are known.

The Steamboat Springs district lying to the east of the Coast Ranges and in Nevada, is only some 9–10 km. distant from the famous silver deposit known as the Comstock Lode. In that district the above-mentioned granite is overlaid by Jurassic and Triassic beds, and intruded and covered by young volcanic rocks, andesite and basalt. To these latter the many springs in the neighbourhood owe their existence. The temperature of these springs reaches nearly to boiling-point, and according to their composition they have given rise to basin-shaped deposits of chalcedony or carbonates, or they have decomposed the granite and at the same time deposited sulphur and cinnabar. The quicksilver content in these mines,

[1] *Ante*, p. 204

which at the moment are not being worked, is said to be not inconsiderable.

The cinnabar of California was long known by the Indians and used by them as a pigment. In 1824 and again in 1835 at New Almaden, by a singular chance it was taken for a silver ore and experimented upon as such. Only in 1845, by Andreas Castillero, was its proper nature recognized. The subsequent mining operations reached their zenith in the 'sixties and 'seventies when these Californian mines produced more quicksilver than Almaden. The highest yearly production was in 1877 when 2700 tons were recovered. Since that date not only has the production of the principal mine New Almaden receded, but this is the case with the others also. Each of the large ore-bodies shown in Fig. 283 yielded from 2800–4500 tons of quicksilver.

The American quicksilver mines deliver their metal to San Francisco ; the European mines to London. These two markets are in close connection, forming together one of the most closely regulated metal markets in the world. Production and price in the United States have been as follows : [1]

Quicksilver Production of United States

Year.	United States.	World.	Price per flask of 34·7 kg. at San Francisco.		
			Highest.	Middle.	Lowest.
	Metric tons.	Metric tons.	$	$	$
1894	1056	3938	37·00	...	27·50
1895	1179	4066	41·00	...	35·90
1896	1036	4020	40·00	...	35·50
1897	965	4328	40·50	...	35·50
1898	1058	4137	42·50	...	38·00
1899	993	3803	52·00	...	47·00
1900	983	3326	52·00	...	45·70
1901	1031	3121	48·50	...	45·00
1902	1208	4073	...	46·51	...
1903	1288	3696	...	44·67	...
1904	1480	3967	32·00	...	34·00
1905	1043	3300	40·50	39·75	38·00
1906	930	3700	41·00	about 41·00	40·00
1907	712	3300	45·00	39·60	38·00
1908	680	...	45·12	44·17	42·25

[1] *Statistical statements of the Metall- und Metallurgische-Gesellschaft*, Frankfort.

Terlingua District, Brewster County, Texas, U.S.

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H. W. Turner. 'The Terlingua Quicksilver Deposits,' Econ. Geol. Vol. I., 1906; further papers are here cited.—W. F. Hillebrand and W. T. Schaller. 'The Mercury Minerals from Terlingua, Texas,' U.S. Geol. Survey, 1909, Bull. 405.

These deposits which have been worked since the 'nineties occur chiefly within a zone about 24 km. long and 3 km. wide, striking east and west, of which the geological section is as follows: Tertiary lavas, in part at least, trachyte; Upper Cretaceous, sandstone and slate; Lower Cretaceous, in greater part thick-slabbed and massive limestone. The ore usually occurs in the limestone, partly in breccia and partly in calcite veins. In the neighbourhood large faults are stated to occur, while dykes of relatively young eruptive rock are also known. Ore has also been met in the Tertiary lavas.

The mineral association here is particularly interesting. As gangue minerals, calcite and selenite occur; quartz however is absent. The ore consists in part of cinnabar with some native quicksilver, but also of a number of new quicksilver minerals, montroydite, HgO; terlinguaite, Hg_2ClO; eglestonite, Hg_4Cl_2O, or $Hg_2O \cdot 2HgCl$; kleinite, a mixture of mercury-ammonium chloride in preponderating amount with an oxychloride and a sulphate or oxysulphate of mercury; and calomel.

Mexico

In Mexico, A. del Castillo counts no less than fifty different deposits and discoveries of quicksilver, most of which are close to young eruptive rocks and in the neighbourhood of silver and gold mines.[1] These deposits, similarly to those in California and along the Peruvian Andes, are also associated with the young Cordilleras; in spite of their number however they have not proved very productive. In former centuries the gold and silver mines of Mexico were forced to procure the quicksilver necessary for amalgamation from Almaden and from Huancavelica in Peru, and the silver output was entirely dependent upon the amount of quicksilver so imported. To-day Mexico still imports this metal.

At the commencement of the 'eighties there was but one mine working in the whole of Mexico; to-day there are several. The best-known among these are the Guadalcazar, Guadalupana, and the Huitzuco mine. The first lies in the State of San Louis Potosi. There, limestone interbedded with clay-slate, both probably of Cretaceous age, are intruded by eruptive rocks.

[1] Map showing the Geology and Ore-Deposits of Mexico by A. del Castillo, 1889.

The limestone is traversed by an irregular network of cinnabar veins, or the cinnabar occurs in nests. Whatever the occurrence, the ore-body is usually separated from the barren rock by a layer of selenite. Calcite, fluorite, and native sulphur, are associated with the cinnabar. The occurrence formerly was important. The Guadalupana mine,[1] also in San Louis Potosi, works a thinly-bedded and stony limestone veined with cinnabar. Up to February 1903, 3520 tons of ore, containing on an average 7·22 per cent of quicksilver, had been won. At Palomas in Durango [2] the cinnabar deposits are connected with the contact between rhyolite and basalt, the first-named having been successively kaolinized, silicified, and impregnated with cinnabar. The more quartzose of the cinnabar veins are characterized by containing bitumen also. The average quicksilver content is given as 0·5 per cent.

The country around Huitzuco in Guerrero consists of metamorphic slate and Cretaceous limestone, both greatly disturbed and lying upon granite. Cinnabar and stibnite occur here in nests and bed-like impregnation zones; more rarely they occur in veins associated with quartz and selenite. According to Pagliucci, quicksilver antimonide has latterly played an important part here. It occurs in an earthy form filling the chimneys of extinct geysers, and in more solid form as veins, nests, and layers, in Cretaceous limestone. Native quicksilver and selenite are of common occurrence. This deposit was discovered in 1874 by an Indian.[3]

The mercury production of Mexico has been as follows: [4]

	Tons.		Tons.
1900 . . .	124	1904 . . .	190
1901 . . .	128	1905 . . .	190
1902 . . .	191	1906 . . .	200
1903 . . .	190	1907 . . .	200

South America

The quicksilver deposits of South America are found in Columbia, Ecuador, Bolivia, Chili, Brazil, Argentine, and Peru. Those of Peru, though now quite subordinate, were formerly so important that Peru among the countries was counted as one of the most productive in this metal. In this production four districts participated, namely: Huancavelica, Yauli, Cerro de Pasco, and Chonta. Of these, Huancavelica on the eastern slope of the Western Cordilleras was formerly almost as important as Almaden.[5]

[1] *Eng. and Min. Jour.*, Mar. 2, 1905; *The Mineral Industry*, 1908.

[2] *The Mineral Industry*, 1907.

[3] J. D. Villavello, 'Genesis de los Saciminetos Mercuriales de Palomas y Huitzuco,' *Mem. S. Alzate*, Mexico, 1903, Vol. 19, p. 95.

[4] *Statistical Statements, Metall- u. Metallurgische-Gesellschaft*, Frankfort, 1909.

[5] Becker, *op. cit.*, p. 21.

According to Crosnier, cinnabar occurs here in Jurassic clay-slate, conglomerate, sandstone, and limestone, striking north-south and dipping steeply to the west. In close proximity to the deposits these sediments are intruded by granite, porphyry, and trachyte, with which intrusions the hot springs now depositing sinter are associated. The most famous mine, the Santa Barbara, working since 1566, exploits a sandstone impregnated with cinnabar, pyrite, arsenopyrite, realgar, calcite, and barite. The total production of this district from 1571 to about 1825 amounted to approximately 52,000 tons of quicksilver.[1]

The district of Yauli lies in a valley of the Andes, north-east of Lima. There, quartz lodes containing cinnabar and pyrite occur in slate and sandstone. In their vicinity hot springs continue to deposit a considerable amount of sulphur. In the silver district of Cerro de Pasco, cinnabar occurs in the neighbourhood of rhyolitic and trachytic lavas. At Chonta in the West Andes a bed of clay and sand, containing pyrite and cinnabar, occurs, the foot-wall portion of which is a sandstone impregnated with cinnabar.

Monte Amiata in Tuscany

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At Monte Amiata the cinnabar deposits occur in close connection with the trachyte which forms the hill of that name. The ore is found in close proximity to this rock in a zone relatively very limited, which extending north-south includes the hill-summit. In that zone the ore-bearing sedimentary rocks are petrographically of very varying character and belong to the most varied formations. At Cornacchino to the west of Castellazzara, they are represented by limestone of the Middle Lias and by limestone and kieselschiefer of the Upper Lias. At Abbadia San Salvatore, in addition to the above rocks, Nummulitic Limestone, Eocene sandstone,

[1] *Ante*, p. 463.

and a clastic rock which occurs between the trachyte and the flat-lying Eocene beds, are included in the occurrence. In the neighbourhood of Monte Vitozzo, Middle and Upper Liassic limestone and kieselschiefer occur again. At Montebuono, Nummulitic Limestone and Eocene sandstone ; at St. Martino, Eocene sandstone ; while finally, at Siele, Solforate, Selva, Cortivecchie, and at numerous other points, Eocene marls are included.

The manner of the occurrence of the cinnabar is likewise most varied. At Cornacchino, shales impregnated with cinnabar, pyrite, and selenite, are found intercalated between limestone beds containing marly flints. These shales probably represent the residual material from dissolved marls, the foot-wall of which, a kieselschiefer, also contains cinnabar to a small extent. The important deposit of Siele between Santa Fiora and Castellazzara, and

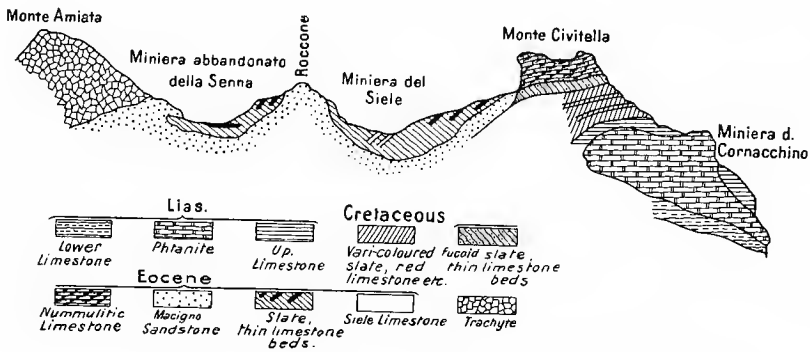

FIG. 284.—Section from Monte Amiata to Miniera de Cornacchino. Spirek.

that of Solforate situated approximately 2 km. to the north, are the residual clays of marly Eocene limestones which contained *Globigerina*, *Rotalia*, and *Coccolites*. Quite close to the Solforate mine, quantities of sulphuretted hydrogen continue to escape from the ground. At Selvagnana east of Samprugnano, and at C. Testi near Montebuono, cinnabar and realgar are found in Nummulitic Limestone ; while at Montebuono itself, the ore occurs as an impregnation in Eocene sandstone and sand. In this last occurrence those portions of the sandstone are particularly rich which were laid down upon a weathered and cavernous surface of limestone. In such a sandstone the mineral occurs evenly distributed in small particles. The limestone for a thickness of about 10 cm. at the contact, is altered to an ochreous material covered with a strongly ferruginous layer which contains cinnabar and crystals of selenite. Famous is that part of the mine known as Il Pozzetto where the limestone is particularly strongly impregnated with cinnabar and altered to an aggregate of calcite, selenite, and cinnabar.

Broadly speaking, this deposit forms a large funnel, the position of which is marked on the surface by a distinct depression.

The detritus which occurs extensively near Abbadia San Salvatore on Monte Amiata, also carries cinnabar. Below this covering the deposits at that place continue in Nummulitic Limestone and trachyte. Rich in quicksilver are some irregular layers of a dark-coloured bituminous shale intercalated between the beds of Nummulitic Limestone. These layers contain small boulders of limestone and fragments of slate in which, ore, partly metasomatic and partly as an impregnation, likewise occurs. Here also cinnabar is accompanied by pyrite. Lotti concedes that this occurrence gives the impression of a primary deposit, yet in view of the preponderance

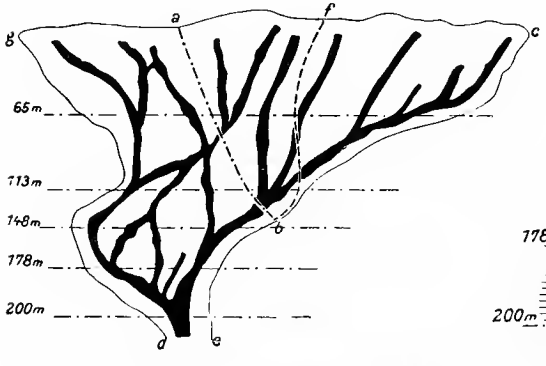

FIG. 285.—Ore chimneys at Monte Amiata projected on the plane of the limestone. Spirek.

abc, Upper limestone bed; *defgfg*, lower limestone bed; *gdec*, limit of the ore-bearing limestone bed.

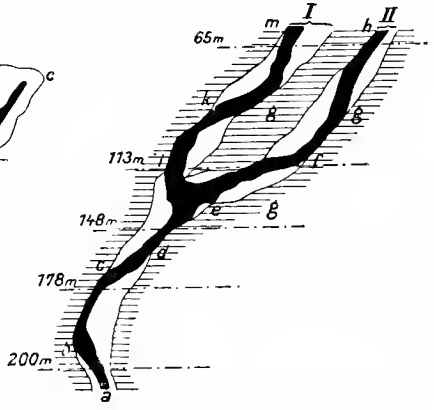

FIG. 286.—Course of the metal solutions in the Siele limestone. Spirek.

I, Upper limestone bed; II, lower limestone bed; *abedimfh*, ore-pipe; *ab*, ore-trunk; *bc*, upper run; *de*, lower run.

of Upper Liassic fragments he regards it as probable[1] that the deposition of cinnabar originally took place in the marly limestone of that period; it appeared to him that the non-aluminous Nummulitic Limestone was less suitable for such an impregnation.

In the so-called *Diecine* the trachyte itself is veined and impregnated by cinnabar, forming a deposit of some importance. The ore here is accompanied by marcasite, opal incrustations, and some calcite, which obviously represent deposition from aqueous solution. At Abbadia a close relation undoubtedly exists between the cinnabar deposits, the emanations of sulphuretted hydrogen, and the acid sulphur-springs in that neighbourhood. The zone subject to these volcanic phenomena

[1] *Zeit. f. prakt. Geol.*, 1901, p. 43.

is about 1·5 km. long in a north-north-east direction, or parallel to the mountain ranges in Tuscany. A further continuation in that direction would pass through the warm sulphur-springs and the selenite masses of San Filippo. This zone according to Lotti coincides with a fault along which the Eocene beds sank to come into juxtaposition with the various Mesozoic members of Monte Zoccolino.

In addition to these cinnabar deposits, quicksilver-antimony ores occur in the district of Monte Amiata and Maremma Grossetana, particularly at the three places, Selvena, San Martino, and Capita. This district extends along the coast in a southerly direction, from Monte Amiata to the vicinity of Capalbio.

At Selvena, west of Cornacchino, black bituminous shales intercalated in Liassic limestone, were formerly worked for the ore with which they were impregnated, this ore consisting of cinnabar, stibnite, realgar, and pyrite. The occurrence at San Martino lies on the right bank of the river Fiora. There, a large mass of crystalline limestone is traversed by veins and nests of stibnite accompanied by calcite and fluorite, while one thin bed consists of cinnabar and limonite.[1] This limestone, which throughout is coloured red by iron oxide, probably represents altered Nummulitic Limestone, and the beds in which it occurs are therefore probably Eocene. At Capalbio near Castellaccio di Capita, an old quicksilver mine works a deposit in Rhaetic limestone close against Eocene beds. At that place radial aggregates of cinnabar, stibnite, and pyrite, occur, chiefly in the Rhaetic but to a smaller extent also in the Eocene.[2]

The Cinnabar Deposit of Vallalta-Sagron

LITERATURE

A. Rzehak. 'Die Zinnoberlagerstätten von Vallalta-Sagron,' Zeit. f. prakt. Geol., 1905, p. 325.

This formerly-worked deposit occurs partly in Italy and partly in the Tyrol. The Valle delle Monache in which it is found, follows a large tectonic line along which conformable Palæozoic and Mesozoic strata dipping to the south have sunk to come into juxtaposition with phyllite. The deposit itself, according to old accounts, occurs in a sandstone accompanied by a red porphyry and embedded in talc-schists, this sandstone being generally light in colour but alternating occasionally with a dark graphitic variety.

Rzehak from his own observations questioned these petrographical

[1] G. B. Rocco, 'Appunti d' una escursione mineraria in Toscana,' *Boll. Comit. geol.*, 1881.

[2] P. Toso, *Revista del Servizio Minerario*, 1895, p. 112.

descriptions. According to him no sharp demarcation between the porphyry and the sandstone can be accepted, more especially as the whole district has been so highly metamorphosed. He considers it highly probable that the occurrence is an isolated, contorted overthrust, whereby a Palæozoic patch now occurs inverted near the contact of Triassic beds with Archæan basement rocks, these latter being represented by the phyllite and talc-schists. There exists consequently a certain analogy between this occurrence and that of Idria where, at all events in the north-west mine, an overthrust also plays a prominent part.

The former importance of this quicksilver occurrence at Vallalta may be gathered from the following figures of production :

	Tons.		Tons.
1863 . . .	16·8	1867 . . .	9·9
1864 . . .	22·4	1868 . . .	12·7
1865 . . .	22·9	1869 . . .	18·3
1866 . . .	17·0	1870 . . .	34·7

Almaden in Spain

LITERATURE

Casiano de Prado. Minas de Almaden. Madrid, 1864; 'Sur la Géologie d'Almaden,' Bull. de la Soc. Géol. Franç., 2e sér., Vol. XII., 1855.—A. Nöggerath. 'Mitteilung über die Quecksilberbergwerke zu Almaden und Almadenejos in Spanien, nebst einem Überblick der Vorkommen von Quecksilber im allgemeinen,' Zeit. f. d. B-, H- u. Salinenwesen im Preussen, 1862, Vol. X. ; 'Joséphe Monastério y Correa,' Rev. Univ. des Min., 1871, 29.—H. Kuss. 'Mém. sur les Mines et Usines d'Almaden,' Ann. des Mines, 7e sér., Vol. XIII., 1878, p. 29 ; 'Note sur l'état actuel de la mine et de l'usine d'Almaden,' Ann. des Mines, 8e sér., Vol. XI., p. 136, Paris, 1887.—R. Helmhacker. 'Ueber den Diabas des Almadenfeldes,' Tscherm. Min. Mitt., 1877.—Caron. 'Bericht über eine Instruktionsreise nach Spanien,' Zeit. f. d. B-, H- u. Salinenwesen im Preussen, 1880, Vol. XXVIII. p. 126.—S. Calderon. Ann. Soc. Espag. Hist. Nat. Vol. XIII., 1884.—G. F. Becker. Loc. cit.—Vogt. Reisebeobachtungen.—H. Pohlig. 'Die Quecksilberlagerstätten von Almaden,' Sitzungsber. Niederrhein. Ges., 1890, p. 115 ; 1892, p. 46.

On the northern slope of the Sierra Morena in the province of Ciudad Real, lies Almaden, the most important quicksilver deposit in the world. The mountainous country around, bare and unproductive, consists of Silurian and to a lesser extent of Devonian beds, which have been subjected to a moderately strong regional metamorphism. The Silurian beds which alone come into consideration in reference to the ore-deposit, consist in their turn of clay-slates, intercalated limestones, and white to reddish quartzites which occasionally pass over to become micaceous sandstones. In the clay-slates occur layers of a schistose diabase tuff, known locally as *Piedra Frailesca* on account of its grey colour which resembles that of the cloak of the Fraile Francisco religious order. Several intrusions of a diabasic or melaphyric eruptive rock are known, while granite, which in depth is probably more extensive, appears at a distance.

Three porous beds of these Silurian quartzites, striking east-west, dipping vertically, and long regarded as lodes, constitute the actual deposits. Upon these three beds, known respectively as San Pedro y San Diego, San Francisco, and San Nicolas, a large number of small mines were formerly scattered. To-day all the work is concentrated at the rich and long-established principal mine in the town of Almaden.

In that mine the three particular quartzite beds have been proved to be impregnated with cinnabar for a length of about 200–250 m. They are separated from one another by bituminous clay-slates, making the distance between the two outside beds just under 50 m. In these clay-slates *Graptolites* have been found. The ore consists chiefly of cinnabar with some

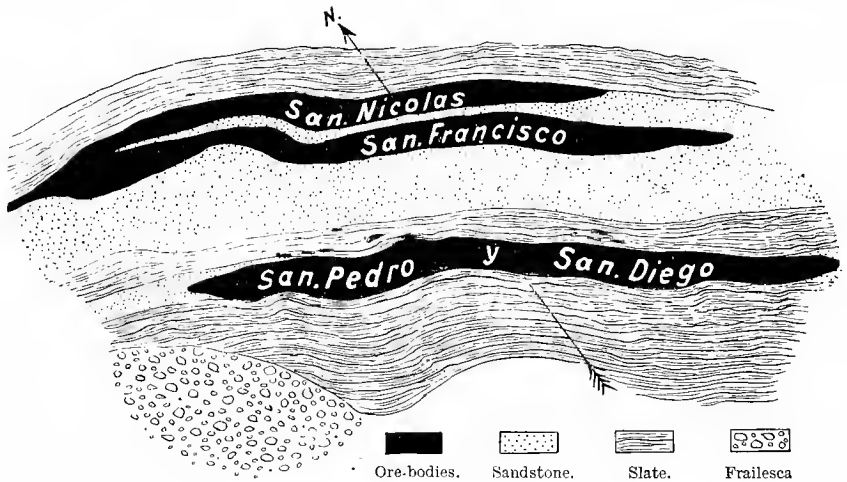

Fig. 287.—Plan of the quicksilver deposit at Almaden. Nöggerath.

metallic quicksilver, a little pyrite, and traces of selenium ; copper, lead, zinc, silver, and gold, are absent ; while gangue minerals are represented by small amounts of barite and dolomite. The cinnabar either occurs filling the pores of the sandstone, the total volume of which pores may in places be as much as 26 per cent that of the rock, or it forms fine veins running in all directions and occasionally enclosing beautiful quartz, barite, or cinnabar druses. At other places the cinnabar actually replaces the substance of the quartzite.

The view that this occurrence of cinnabar is to be regarded as an impregnation of lode-like and not of sedimentary character is confirmed by the fact that the ore has nowhere found its way into the impermeable clay-slates. Whether the quicksilver solutions necessary to this assumption

were in any way genetically related to the neighbouring eruptives must remain an open question.

The principal bed attains a width of 8–14 m. with an average quicksilver content of 14–15 per cent. The other two, the San Nicolas and the San Francisco, somewhat darker in colour, are less wide and carry

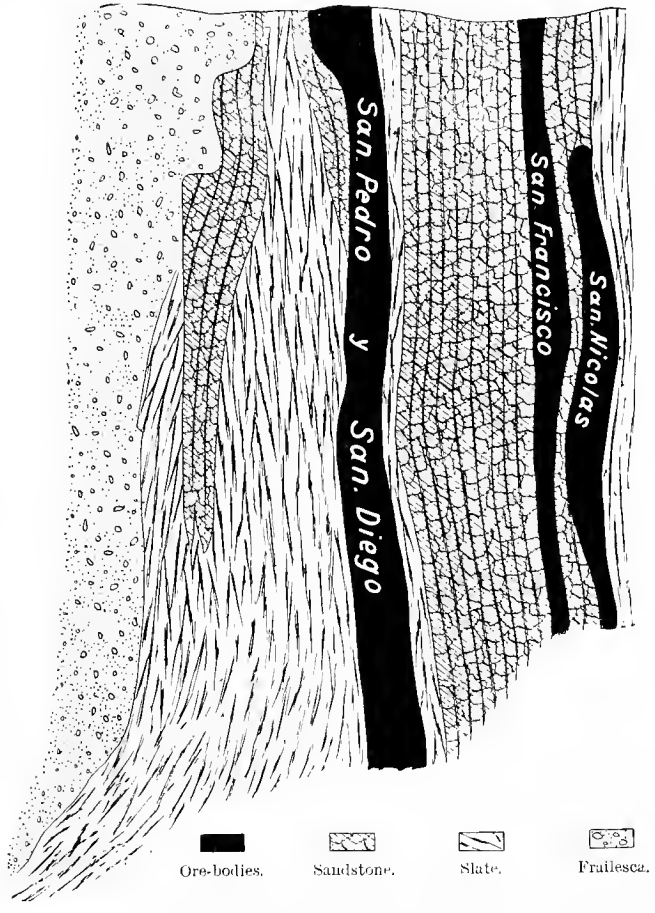

Fig. 288.—Section through the quicksilver deposit at Almaden. Monasterio y Correa.

poorer ore, some of it containing as little as 2·5 per cent. The average content of the material mined, which at the beginning of the 'fifties and 'seventies was about 7 per cent, is now about 8 per cent; and the mine in spite of centuries of uninterrupted work is yet only 350–375 m. deep.

The production of this, the richest and most profitable of all the quicksilver deposits yet known and a veritable nest-egg to the Spanish Exchequer,

is regulated according to the demand of the decidedly small market for quicksilver. Of the world's yearly production amounting to 3500–4000 tons, some 900–1400 tons is contributed by this mine. In the eighteenth century and in the first half of last century, the Californian deposits not yet having been discovered, the proportion was still higher; Almaden then supplied more than one-half of the total production.[1]

According to Nöggerath, the total working cost from 1850–1854 amounted to about 1s. 9d. per kg. delivered at London; and from 1870–1875 to about 1s. to 1s. 2½d.; while more recently it has been given as 10d. or 11d. Against this cost the average selling price during the last fifty years may be taken to have varied between 3s. 6d. and 5s. per kg. Estimating the total production of Almaden between 1564 and 1907 at 169,000 tons of quicksilver and putting the average price during this whole period at 5s. per kg. this production represents a total value of about £42,500,000. Before this period it was worked by the Romans who applied the quicksilver they obtained to the making of pigments. For comparison the productions of some other old and famous mines are here quoted:

Kongsberg, Norway, 1624–1908	about	£8,000,000
Almaden, Spain, 1564–1907	,,	42,500,000
Freiberg, Saxony, 1163–1890	,,	44,400,000
Comstock, Nevada, 1859–1898	,,	70,000,000
Veta Madre, Mexico, 1558–1820	,,	100,000,000
Veta Grande, Mexico, 1548–1832	,,	125,000,000

According to these figures quite a number of mines have surpassed Almaden in the gross value of their total production. Never however has there been any important mine where the relation of the net profit to the total yield has been so high.

The quicksilver production of Spain which is practically speaking that of Almaden, has been as follows:

	Tons.		Tons.
1900	1095	1904	1058
1901	754	1905	834
1902	1425	1906	1300
1903	968	1907	1212

There are in Spain in addition other occurrences of quicksilver, as at Mieres in the Asturias on the southern borders of the Sierra Nevada, and at La Creu in the province of Valencia. At Mieres the deposit occurs in Carboniferous sandstone and slate; a breccia formed of fragments of these beds carries cinnabar, pyrite, arsenopyrite, and realgar in fractures, cavities, and impregnations, the deposit is 65 feet wide and several kilometres long; the production of El Provenir and other mines during

[1] *Ante*, p. 468.

1893 was some 100 tons of quicksilver. In the neighbourhood of La Creu veins consisting of an intimate mixture of cinnabar, quartz, and carbonates, are found occurring in sandstone.

Portugal at the end of last century still produced some quicksilver.

Idria in Krain

LITERATURE

Das k. k. Quecksilberwerk zu Idria in Krain. Published by the management, Vienna, 1881.—M. V. Lipold. 'Mitteilungen über die geologischen Verhältnisse der Umgegend von Idria,' Jahresber. d. k. k. Geol. Reichsanst. IV., 1853, pp. 422 and 864; VII., 1856, p. 838; VIII., 1857, pp. 205, 385, and 760; IX., 1858, Verhandl., p. 18; XXIV., 1874; Erläuterung zur geologischen Karte der Umgegend von Idria, p. 425; XXIX., 1879. Verhandl., p. 186.—R. Meier. 'Ueber den Quecksilberbergbau von Idria,' Verhandl. d. k. k. Geol. Reichsanst., 1868, p. 122.—E. von Jahn. 'Ueber das Idrianer Korrallenerz,' ibid., 1870, p. 203.—D. Stur. 'Geologische Verhältnisse des Kessels von Idria,' ibid., 1872, p. 235.—F. Gröger. 'Zum Vorkommen der Quecksilbererze,' ibid., 1876, p. 67.—C. von Ernst. 'Ueber Quecksilber' Oesterr., Zeit. f. Berg- u. Hüttenw., 1877, Vol. XXV. p. 75.—F. Gröger. 'Der Idrianer Silberschiefer,' Verhandl. der Geol. Reichsanst., 1879, p. 105.—A. Schrauf. 'Über Metacinnabarit von Idria und dessen Paragenesis,' Jahrb. d. Geol. Reichsanst., 41, p. 349, Vienna, 1891; reviewed in Groths Zeit. XXI., p. 283.—E. Suess. Sitzungsbericht der Wiener Akademie der Wissenschaften, LVII., I., p. 791; Geol. and Min. Maps of Idria with sections and drawings of the quicksilver deposits; surveyed by government officials; text by Plamineck. Vienna, 1893. Published by the Minister for Agriculture.—F. Kossmat. 'Über die geologischen Verhältnisse des Bergbaugebietes von Idria,' with 2 plates, Jahrb. d. k. k. Geol. Reichsanst., Vienna, 1899, Vol. XLIX., Pt. 2.—T. L. Genter. 'The Quicksilver mines of Idria,' Eng. and Min. Jour., 1903, Vol. LXXVI., p. 923.

The geology of the country around Idria, a town situated on a river of the same name upon the south-eastern foot-hills of the Juli Alps, has in its essential features been made clear by the investigations of Lipold. In this district Carboniferous beds represented by the Gailtal slates deserve first mention. These consist partly of fissile dark grey clay-slates and partly of fine-grained dark sandstones, these latter containing argillaceous binding-material and such plant-remains as *Calamites Suckowi*, *Dictyopteris Brongniarti*, *Sagenaria*, etc. These slates, known on the mines as *Silberschiefer*, are in places against the quicksilver deposit impregnated with native quicksilver. They form a narrow north-west to south-east belt following a zone of disturbance more closely described below, and are overlaid by representatives of the Permian and Triassic formations, among which the most important are the Werfen beds with the Gröden sandstone, and the Seisser beds of South Tyrol. Upon these follow the Guttenstein limestone; then the Wengen beds consisting of dark slate, conglomerate, and tuff, the last being represented by the Skonza beds; then the Cassian beds; and finally the Lunz or Raibl beds. Above the Triassic again, other Cretaceous and Eocene formations are found. The ore is associated with the Werfen

and Guttenstein beds of the Lower Triassic, and with the Wengen and Skonza beds of the Upper Triassic. It is further associated with a large zone of disturbance which may be followed on surface from the Kalomla Valley over Raspotje into the hollow at Idria, and from there south-east through the Idria Valley. This zone marks the occurrence of an overthrust along which the older Carboniferous beds were pushed up over the younger and much contorted Triassic strata. One or two more or less parallel disturbances accompany this powerful overthrust.

The occurrence of the ore to the north-west, in the Barbara and Theresia properties, is quite different from that in the Josephy property to the south-east. In the former the ore is concentrated in the Skonza beds and occurs but little in the calcareous conglomerate above. The ore-body has then the form of a true bed 20 m. thick with the foot-wall generally formed by the Wengen tuff but also at times by the Guttenstein limestone. The hanging-wall calcareous conglomerate is in places also impregnated with cinnabar. The ore content in these Skonza beds is rendered extremely irregular and fluctuating by the occurrence of lenticular patches and impregnations.

The occurrence in the Josephy property is quite different. At this place numerous faults striking roughly E.N.E. and dipping 28–30°, are for a width of 1 m. filled with limestone fragments cemented together by cinnabar. Other faults, without ore and striking roughly E.S.E., cause an enrichment where they intersect the E.N.E. faults, an enrichment which is not limited to the fissure-fillings but is expressed also by an impregnation of the walls. By far the greatest portion of the ore consists of cinnabar; native mercury occurs occasionally but only in the *Silberschiefer*. Four classes of ore are usually distinguished: (1) stahlerz, containing 75 per cent of quicksilver; (2) lebererz, often forming the kernals of stahlerz; (3) ziegelerz, always occurring at the margins of the deposit; and (4) korallenerz, with 56 per cent of lime phosphate, 2 per cent of cinnabar, and 5 per cent of bitumen. Pyrite, fluorite, dolomite, epsomite, selenite, together with some quartz and calcite, occur to a lesser extent.

Concerning the genesis of this deposit there can also in this case be no doubt that the ore was deposited from aqueous solution. Both the connection with the large overthrust and the occurrence of ore in various beds, in part filling fissures and in part forming impregnations, confirm this view. Since the large overthrust is certainly younger than Cretaceous and may possibly have been formed in Quaternary times, the deposit geologically speaking may be quite recent.

The present annual production amounts to about 60,000 tons of ore containing about 530 tons of metallic quicksilver.[1] About 800 men are

[1] *Ante*, p. 463.

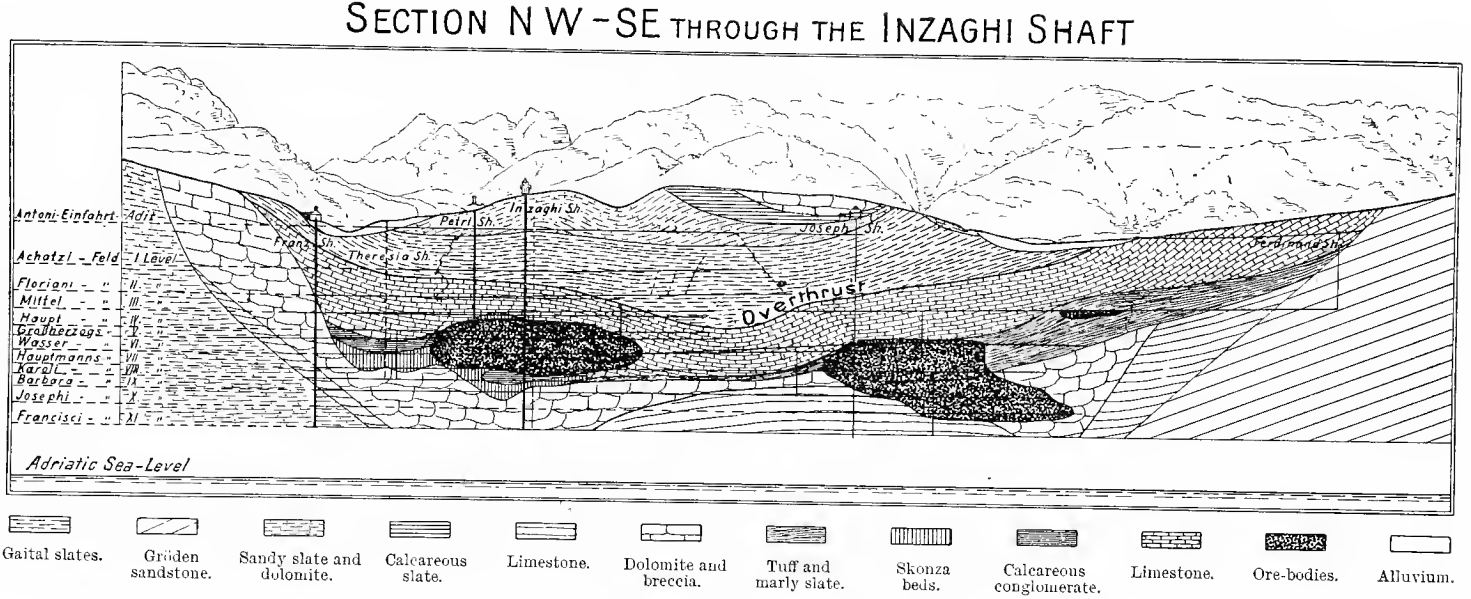

FIG. 289.—Section through the quicksilver deposit at Idria.

employed, and the profit flowing yearly into the State Exchequer is about £25,000. The amount of quicksilver still reckoned to be contained in the deposit is estimated at about 30,000 tons. The production of Austria-Hungary, which is almost all obtained from Idria, has latterly been as follows:

	Tons.		Tons.
1900	550	1905	570
1901	567	1906	577
1902	563	1907	610
1903	575	1908	630
1904	550		

Some of the smaller deposits in Hungary are interesting in that they contain quicksilver-bearing tetrahedrite from which in the oxidation zone cinnabar results, this mineral being there accompanied by amalgam, pyrite, quartz, and barite. Such deposits occur at Iglo and Dobschau in the Carpathians, where the tetrahedrite contains up to 16·7 per cent of quicksilver. The veins are found in old slates. The quicksilver is won as a by-product when roasting the tetrahedrite. Again in the Thihu valley, also in the Carpathians, a zone filled with calcite, dolomite, and rock fragments, and occurring between a lava sheet and a much altered clay-slate, carries veins and nests containing cinnabar, galena, and sphalerite.

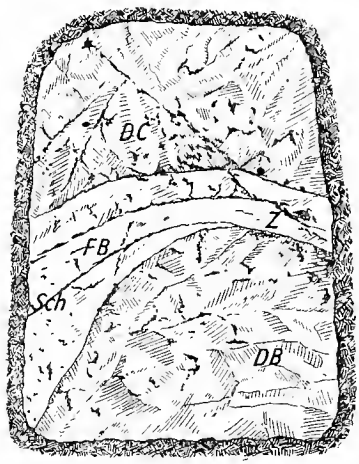

FIG. 290.—Appearance of the deposit in the face about 75 m. north-west of the Inzaghi Shaft. Idria.

Z, Cinnabar; *Sch*, schistose parting; *FB*, friction breccia; *DC*, dolomite-conglomerate; *DB*, dolomite breccia.

The production of Hungary in the 'eighties was only about 10 tons per year, since when it has been even less. Other figures of production have already been given.[1] In Bohemia the iron deposits at Horovik contain small amounts of cinnabar, quicksilver, and calomel.

[1] *Ante*, p. 463.

Quicksilver Occurrences in Germany

LITERATURE

H. von Dechen. 'Das Vorkommen der Quecksilbererze in dem Pfälzisch-Saarbrückenschen Kohlengebirge,' Karstens Archiv, 1848, Vol. XXII., pp. 375-464.—W. von Gümbel. 'Ueber die Quecksilbererze in der Pfalz,' Verh. d. naturh. Ver. f. Rheinl. u. Westf., VII., 1850, p. 83; Geologie von Bayern, II. pp. 959-980.

Germany to-day in relation to its production of quicksilver occupies a subordinate position among European countries. The occurrences at Moschellandsberg, Potzberg, and Kirchheimbolanden in the Pfalz, are only interesting historically and geologically. The ore, chiefly cinnabar, occurs generally in veins and associated impregnations in sandstone, conglomerate, and clay-slate, belonging to the Ottweil beds, these being the uppermost beds of the Coal-measures. Some deposits however occur also in melaphyre and porphyry. Where the veins traverse ore-bearing sandstone and clay-slate these rocks are altered to masses resembling hornstone and argillite respectively. The deposits which have been followed for the greatest lengths are the Gottesgaben Lode on the Landsberg, and the Alten-Werk Lode, these having been proved for 900 m. and 400 m. respectively. In these two cases the quicksilver content, which in the upper levels was considerable, diminished so rapidly in depth that the deepest stopes do not reach 200 m. below the surface. The fissure-filling consists of clay with nests of cinnabar, native quicksilver, amalgam, calomel, metacinnabarite, some pyrite possibly, tetrahedrite, and stibnite, with calcite, barite, quartz, and red silex, as gangue. It is known definitely that these deposits in part were already working as far back as the commencement of the fifteenth century. In the eighteenth century particularly, they were quite important, though now they are of little interest. The quicksilver ores associated with quartz at Neustadt in Bavaria and Lössnitz in Saxony, are similarly of no economical importance.

The Quicksilver Deposit at Avalaberg Near Belgrade

LITERATURE

A. von Groddeck. 'Über das Vorkommen von Quecksilbererzen am Avalaberg bei Belgrad in Serbien,' Zeit. f. d. B-, H- u. Salinenwesen in Preussen, 1885, Vol. XXXIII. p. 112.—H. Fischer. 'Die Quecksilberlagerstätten am Avalaberge in Serbien,' Zeit. f. prakt. Geol., 1906, p. 125.

The Avala hill, 320 m. high, situated 20 km. south of Belgrade, consists chiefly of non-fossiliferous marly limestones, presumably of Cretaceous age, which are intruded by trachyte dykes. At the foot of the hill magnetite

and chromite, finely distributed in a rhombic pyroxenic serpentine, occur plentifully. This rock, which presumably has been formed by the decomposition of an enstatite-olivine rock, attains greater proportions farther to the south.

The wide belt of country around the hill consists likewise of marly limestone and serpentine. In the serpentine area to the south, at Schuplja Stena, Djewer Kamen near Rupine, Mala Stena, and Kamen No. 2, quicksilver deposits occur having pronounced outcrops. According to von Groddeck the ore-bearing area has a length of 1300 m., and a width of 800 m. At the southern limit of the serpentine against the marly limestone is a wide bar easily followed by its rocky outcrop and known as the 'lower lode.' This likewise carries traces of cinnabar and some galena.

The serpentine in the neighbourhood of the Avala hill is in part completely altered, so that to-day a replacement pseudomorph consisting of quartz, opal, and dolomite after serpentine, is presented. The limonite found filling the cavities in this quartz-rock probably represents the ferruginous residue of the serpentine. The origin of these skeleton crystals of quartz which possess great similarity to the 'red-rock' of the garmierite deposits, is probably referable to thermal action.

The quicksilver minerals occur exclusively in this porous quartz-rock to which fact the ore-bodies owe their capacity to appear so strongly at the surface. They include cinnabar and native quicksilver, often in considerable amount, and calomel. Cinnabar is found either as fine dust in the siliceous skeletons of the decomposed serpentine, or it serves as the binding material of angular fragments of that rock. It also occurs as a coating in veins of quartz and felspar, or finally in solid masses. With it some pyrite is almost invariably present.

These deposits, for which von Groddeck prophesied a great future, have not fulfilled the expectations created. The production during the period 1885–1891 was only 7796 tons of ore with an average content of 1·02 per cent of quicksilver.[1]

Relative to the genesis of these deposits the authors believe that the origin of the skeleton crystals of silica and dolomite must be considered separately from that of the quicksilver. The thermal waters to which the decomposition of the serpentine is ascribed, as well as the young quicksilver solutions, were both probably consequent upon the intrusion of the trachyte magma.

[1] J. Antula, *L'Industrie minérale de Serbie*, 1905.

The Quicksilver Deposits of Russia

LITERATURE

C. von Ernst. 'Das neue russische Quecksilberwerk bei Nikitovka,' Öster. Zeit. f. d. B- u. Hüttenwesen, 1889, Vol. 37, p. 430; Guide des excursions du VII. Congrès Intern. Géologique, 1897, XVI., pp. 36-45.

The Russian quicksilver deposits belong partly to Europe and partly to Asia. Those in Europe are found at Nikitovka and Gavrilovka, in clay-slate overlaid by Carboniferous sandstone, and in coal-seams. The cinnabar is found in crevices and in extensive impregnation zones in the porous sandstone. Since several hundred tons of quicksilver have been won from them yearly these deposits must be considered to have been of some importance. As will be seen however from the statement below, the production for the year 1908, probably owing to the irregular distribution of the ore, fell remarkably.

The mines of Ildekansk near Nertschink in Eastern Siberia are in so far interesting that during the time they were being worked, 1759–1853, heartrending stories of the tremendous mortality of the convicts employed, were circulated. It is however the case that work in quicksilver mines, where no metallic quicksilver is found, is no more dangerous than work in any other mine. The ore occurs in inconsiderable amount in veins and nests in yellowish grey limestone with calcite and quartz. At no time were many people employed.

Leaving out of consideration the little-known occurrences of Kamtschatka, quicksilver also occurs in the Ural gold district near Beresowsk, Miask, and Bogoslowsk. At these places no primary deposits have yet been found, the cinnabar occurring with the gold in gravels. Judging from the fact that pieces of cinnabar up to 1·5 lbs. in weight have been found, the original primary deposits must in part at least have been of considerable size. The production from Russia, most of which comes from Nikitovka, may be gathered from the following figures:

	Tons.		Tons.
1900	304	1905	318
1901	363	1906	210
1902	416	1907	130
1903	362	1908	49
1904	332		

Deposits in Asia Minor

The ores at the Koniah mine occur in limestone [1] where their association with the silicified sections of that rock is so pronounced that the silica and cinnabar have probably been derived from some common source. The ore-bodies thus occurring are traversed by narrow veins of cinnabar. The payable ore contains usually 1–2·5 per cent of quicksilver, though one large

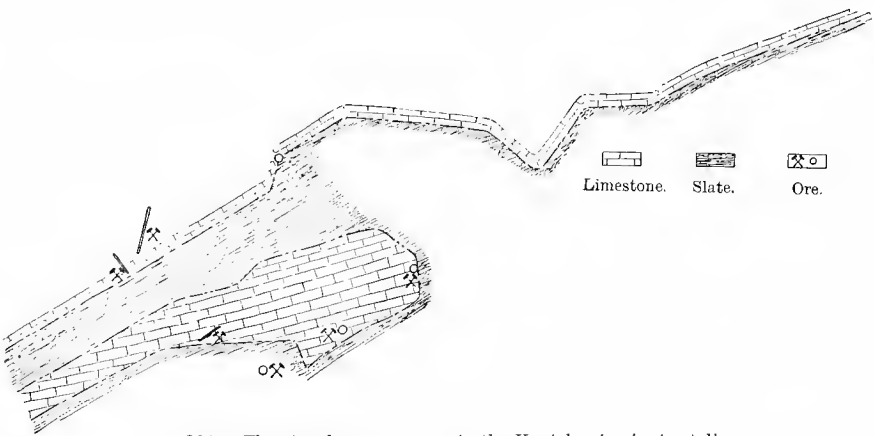

Fig. 291.—The cinnabar occurrence in the Koniah mine in Anatolia.

section associated with stibnite contained as much as 8 per cent. According to F. P. Monaci, approximately 13,000 tons of 1 per cent ore now stand developed and ready for stoping.[2] According to the same authority the Kara Bournu mine, situated 32 km. from Smyrna, works in opencut a rock impregnated with an average of 0·75 per cent quicksilver, the lower limit of payability being here about 0·25 per cent. The production in 1906–1907 amounted to about 3000 flasks.

Deposits Elsewhere

The deposits at Kwei Chan in China are little known. Apparently however they are rich, as von Richthofen states that China has at times been in the position to export quicksilver. At the Wan Shan Chang mines in the Toon Yen prefecture, the ore occurs in almost horizontal bed-like bodies in dolomitic limestone, either impregnating definite beds; or as deposits

[1] F. F. Sharpless, *Eng. and Min. Jour.* LXXXVI. p. 601; *The Min. Indus.*, 1908, p. 746.

[2] *Rassegna mineraria*, April 11, 1908.

in fractures, crevices, nests, or bedding-planes; or finally, irregularly impregnating certain highly disturbed strata.[1] The cinnabar is either pure or associated with antimony. The production is greatly affected by the frequency of the floods and pestilences which visit the district.

Upon the island Hirado belonging to Japan, cinnabar occurs in an impregnated bed of Carboniferous sandstone. On Mount Tagora in Borneo it occurs in veins and impregnations in sandstones accompanied by slates, with which primary occurrence the occurrence of cinnabar in gravels is also associated. At Philippeville in Algiers cinnabar occurs in Nummulitic Limestone at the contact with clay-slate; while the deposits of Taghit and Palestro occur in Cretaceous beds.

The deposits in New Zealand are particularly interesting in that they stand in traceable connection with hot springs. Two warm sulphur-springs wend their way through sandstone which they have impregnated with quicksilver. In one fissure $\frac{1}{4}$–$\frac{1}{2}$ in. thick, where thermal water circulates, the sides are coated with quicksilver minerals, sulphur beads, and beads of metallic quicksilver.

Des Cloiseaux in the sinter of the large geyser of Iceland found metallic quicksilver, an occurrence however which Bunsen regarded as accidental and probably derived from a broken thermometer or barometer.

[1] *The Min. Ind.*, 1908, p. 747.

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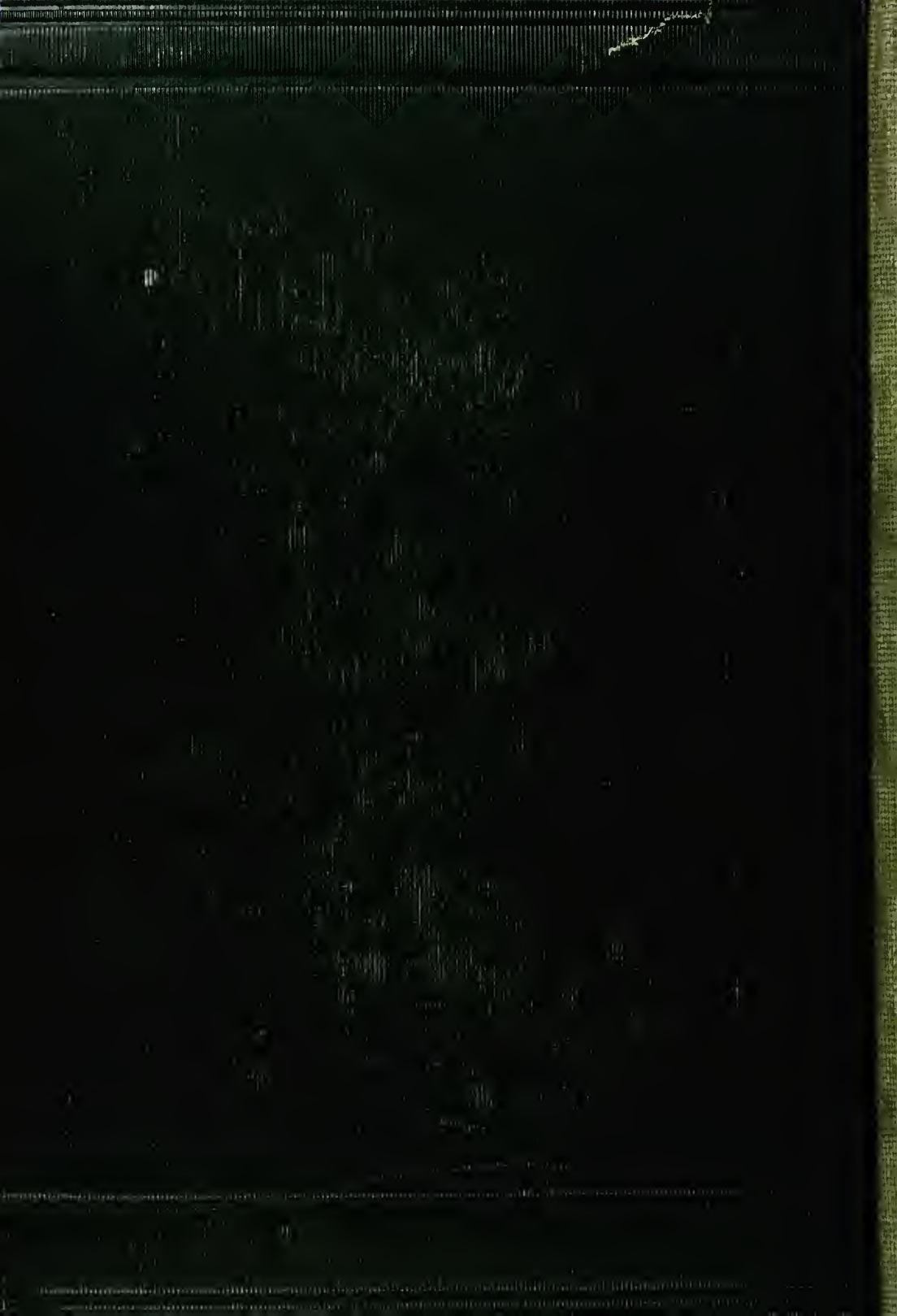
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